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## MORPHOLOGY AND ANATOMY OF THE NORWOOD ESKER, ONTARIO

By

JOHN ARTHUR DIXON

## ABSTRACT

Over its 25 km. length the Norwood esker traverses two morphologically different areas, a northern section of kame, and a southern section of elongated drumlins. In the north the esker consists of single and multiple ridges: where multiple, the ridges are superimposed on a lower, broader, plateau-like base. In the south a high, steep-sided single ridge is present. In both areas, where single, the ridge splits locally into two narrower ridges which rejoin a short distance downstream.

Internally, the esker contains mostly cross-laminated sands, trough-shaped and tabular sets of cross-bedded sands and gravels, and matrix-supported sandy gravels. The cross-laminated sands occur most frequently on the flanks of northern sections and at high stratigraphic levels in the southern. The cross-bedded sands and gravels make up most of the core: in the north they are overlain by matrix-supported sandy gravels and in the south by cross-laminated sands.

The results of the investigation indicate that:

- a) the Norwood esker formed within a subglacial tunnel that was flowing full near the end of ablation as indicated by the upper stratigraphic position of the sliding bed,
- b) the larger, more complex ridge system of the Norwood esker developed within a well integrated system of channels,
- c) the granule layer that formed between layers of fine sand marks an erosional boundary separating sequences of lower flow velocity, and as such may provide a clue to the number of depositional units, possibly related to diurnal, seasonal and cyclonic effects on discharge,
- d) the fact that the sliding bed is present as two separate layers within the sedimentary column of the esker indicates that it is likely a frequent mode of transport within en- and subglacial channels.

MORPHOLOGY AND ANATOMY OF THE NORWOOD ESKER, ONTARIO

By

JOHN ARTHUR DIXON  
B.A. Wilfrid Laurier University, 1976

THESIS

Submitted in partial fulfilment of the requirements  
for the Master of Arts degree  
Wilfrid Laurier University  
1978

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## CHAPTER I

### INTRODUCTION

One of the long term problems of geomorphology has been its inability to establish the exact mode of origin of glacial depositional features like the esker. The basic forms of esker deposits are well known and are described in texts such as Flint(1971) as being long, sometimes sinuous, often segmented, ridges of sands and gravels that were deposited in an ice-contact environment, either supraglacially, englacially or subglacially. Yet we cannot confirm which of these positions the channel occupied simply from morphological information alone.

Internally, most eskers consist of cross-bedded gravels and sands. This has been known for a great many years, (for a review of initial glacio-fluvial studies see Jopling, 1975), but not until recently have accurate interpretations of these deposits been

possible. Hjulstrom's (1935) work on the flow velocities required to initiate and maintain movement of specific grain sizes provided valuable information for subsequent research in this line, with the work of Allen (1965), Jopling (1965), Simons, Richardson and Nordin (1965), Jopling and Walker (1968) probably being most noteworthy on the mode of origin of primary sedimentary structures in the sand size range. Southard (1971) provides information on the alteration of the sequence of bedforms as the grain size increases from sand to gravel.

The knowledge of the origin of primary sedimentary structures has been used by many authors in an attempt to identify the depositional environment for esker deposits (Shaw, 1972; Banerjee and McDonald, 1975; Saunderson, 1975a). This knowledge, coupled with the morphological information like the presence or absence of kettle holes or the trend of the esker across bedrock valleys, has been employed to identify the position of the esker channel on, in, or under the ice mass. Unfortunately, these morphological indicators do not completely confirm the position of the tunnel, for till may not be present on the esker ridge if a) no till was laid down, or b) the channel was full of water at the time of deposition, modifying any till laid

down. However, till may cover the ridge if it formed in a crevasse as an open channel and a till was deposited over the ridge due to collapse of the ice walls.

Obviously, some unique condition of flow is needed in order to resolve this problem. McDonald and Vincent(1972) performed an experiment on sand moving in a pipe flowing full of water and suggested that it might be applied to esker deposits. Their reasoning was based on the fact that bedforms within pipes are not exactly the same as those formed in open channels, the anti-dunes and chutes and pools being absent in pipes. However, it was not until Saunderson(1977b) that the application of this situation was made.

Saunderson(1977b) analysed the engineering literature on pipe flow and found that reference was continually being made to a sliding bed at high values of bed shear stress. This bedform develops at similar Froude numbers to the anti-dunes of Simons et al (1965). However, anti-dunes do not form in pipes flowing full because of the lack of surface waves (Acaroglu and Graf, 1968). Saunderson(1977b) suggests that the sliding bed is present within the Guelph esker and therefore indicates flow in a sub- or englacial channel. However, if the deposit was englacial in nature, it would likely be severely distorted as it was



let down by the ablating ice thus implying a subglacial position for the ridge.

### 1.1 Purpose of the Study and Choice of Field Area

The purpose of the present study will be to describe the morphology and internal structure of the Norwood esker, thereby adding to the information on esker deposits which are still only poorly understood. Interpretations of morphology and structure will be based on theories of sediment transport for open-channel and closed-conduit flow.

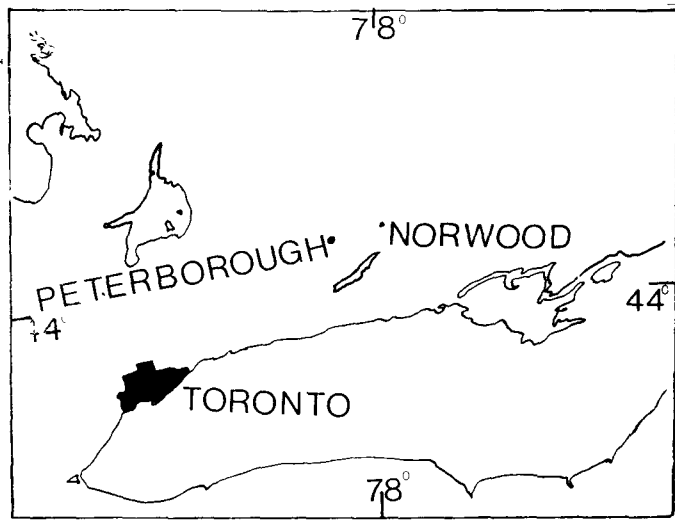
The Norwood esker was selected as the field site for a number of reasons. Firstly, because of its overall size, both in height and length, it ranks as one of the largest eskers in Southern Ontario, making it of importance to study. Secondly, because of the number and distribution of exposures available, it was possible to obtain a picture of the entire esker complex. Finally, a number of esker types have been examined in other areas; the relation of these to the Norwood esker is therefore of importance.

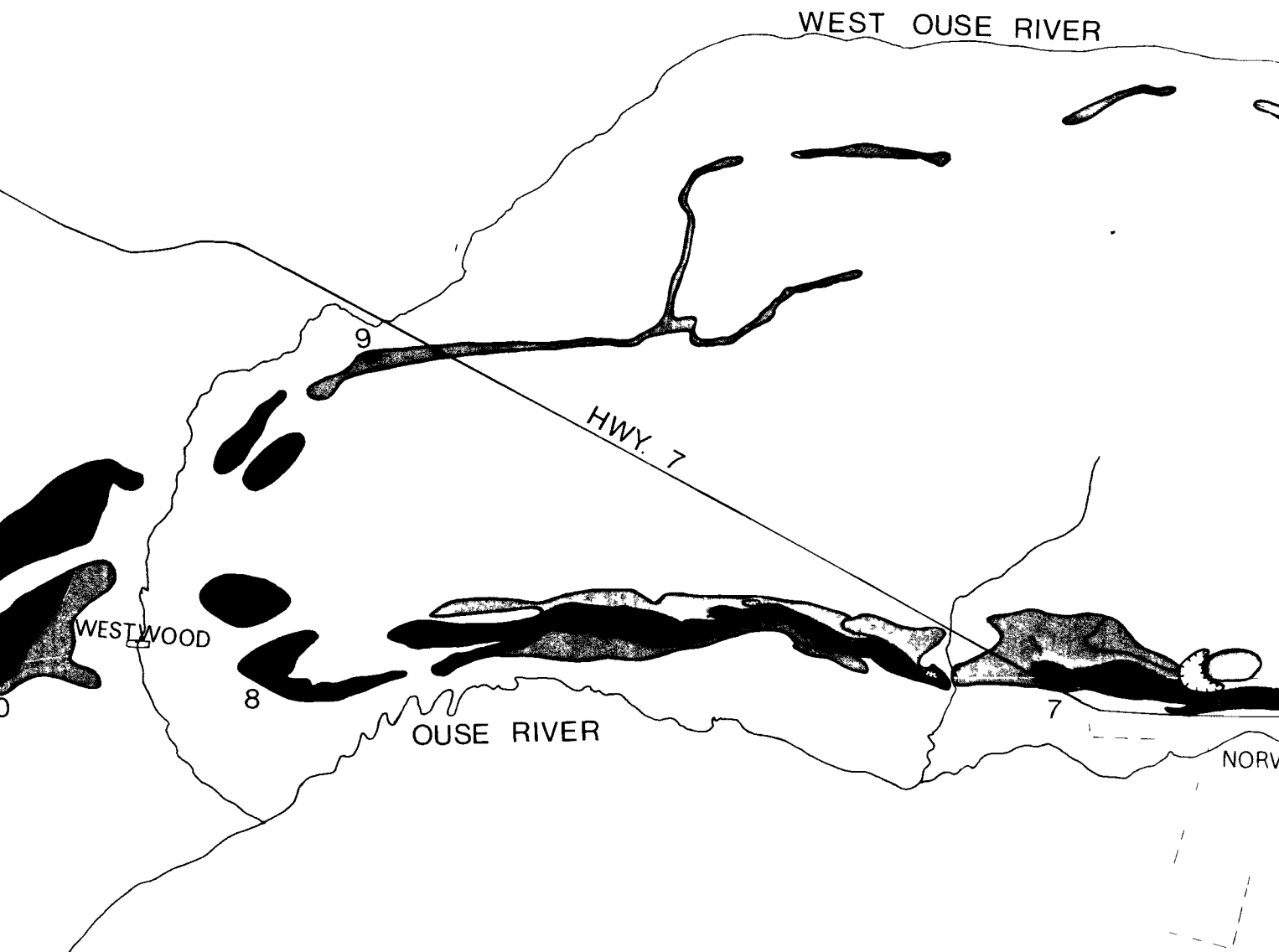
## 1.2 Location of the Study Area

The Norwood esker, located 156km northeast of Toronto and 27km east of Peterborough, has its beginnings just east of Havelock. From here it extends some 25km to the southwest and terminates on the shores of Rice Lake (fig.1). The esker is generally located in what Chapman and Putnam (1966) have called the Peterborough drumlin field. Closer inspection of the area however, reveals that the northern portion is located in kame and only the southern portion is actually within the drumlin field.

## 1.3 Bedrock Geology of the Study Area

Most of the bedrock in the area consists of sedimentary rock; primarily Paleozoic limestones, dolomites or shales. The area just to the north of Havelock however, has outcroppings of Precambrian rocks primarily granite, granite pegmatite, diorite, and gabbro. Volcanics are also represented here with acidic types including rhyolite and tuff and basic types including andesite and basalt; just east of Havelock, a large basalt mine is currently in operation.





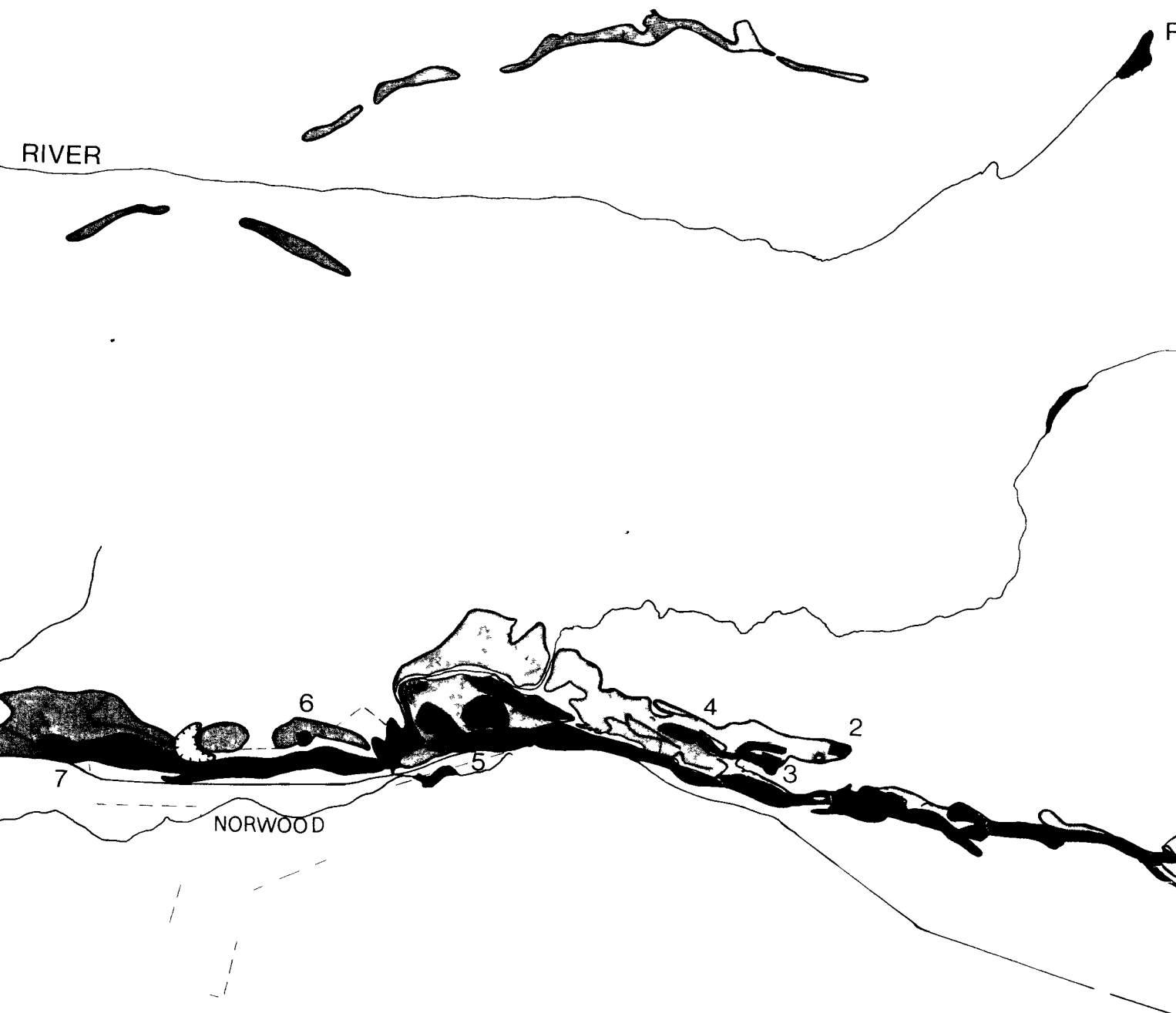
# NORWOOD ESKER

RIDGE ELEVATION  
■ HIGH  
▨ LOW

0 2 KM.

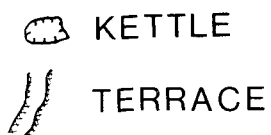


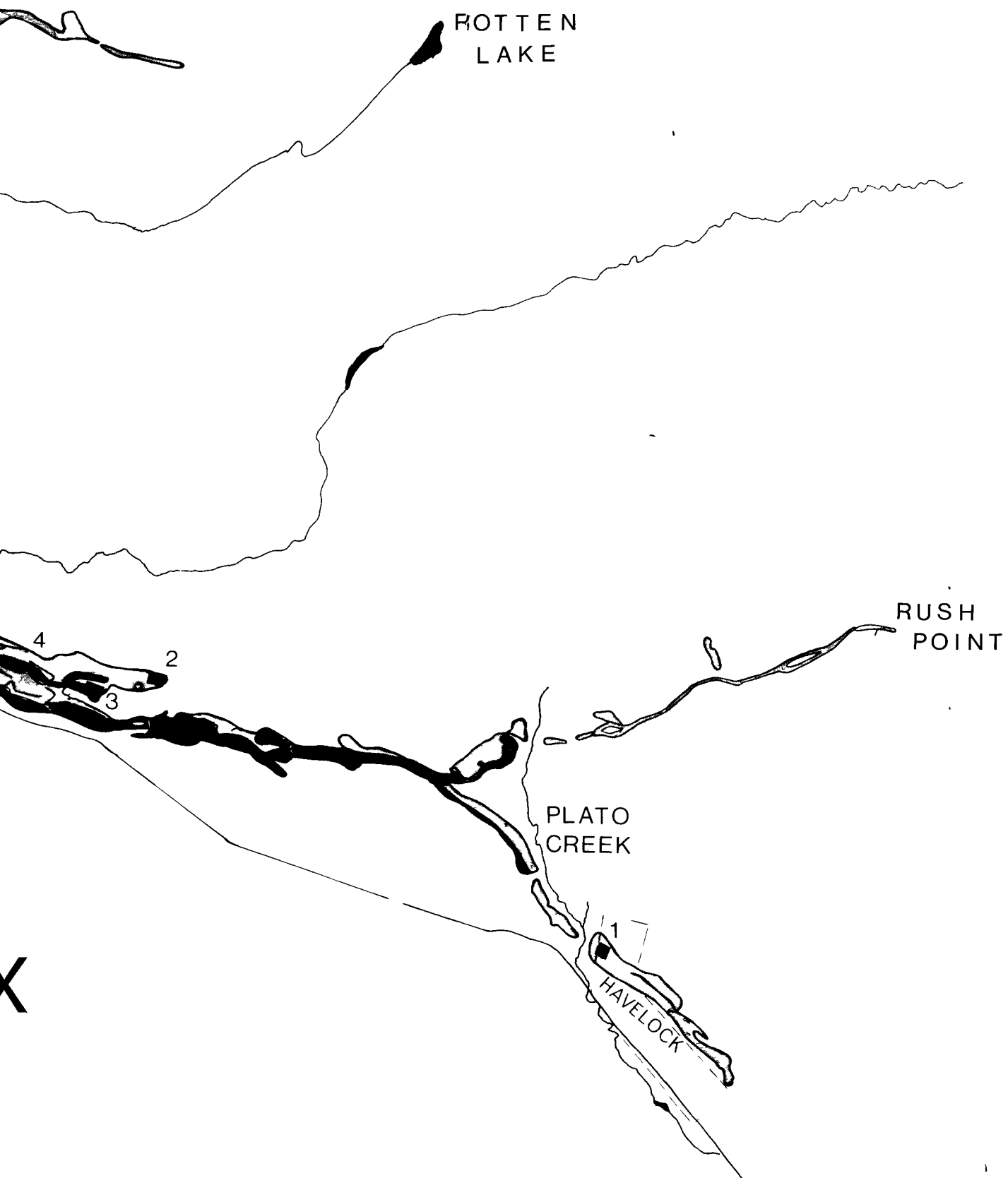
● K  
— T



# SKER COMPLEX

KM





Because of the position of the Precambrian outcrops, just northeast of Havelock, and the fact that the ice mass moved from north to south, the sediments within the esker and the surrounding area contain sedimentary and crystalline clasts of Palaeozoic and Precambrian age (fig.2).

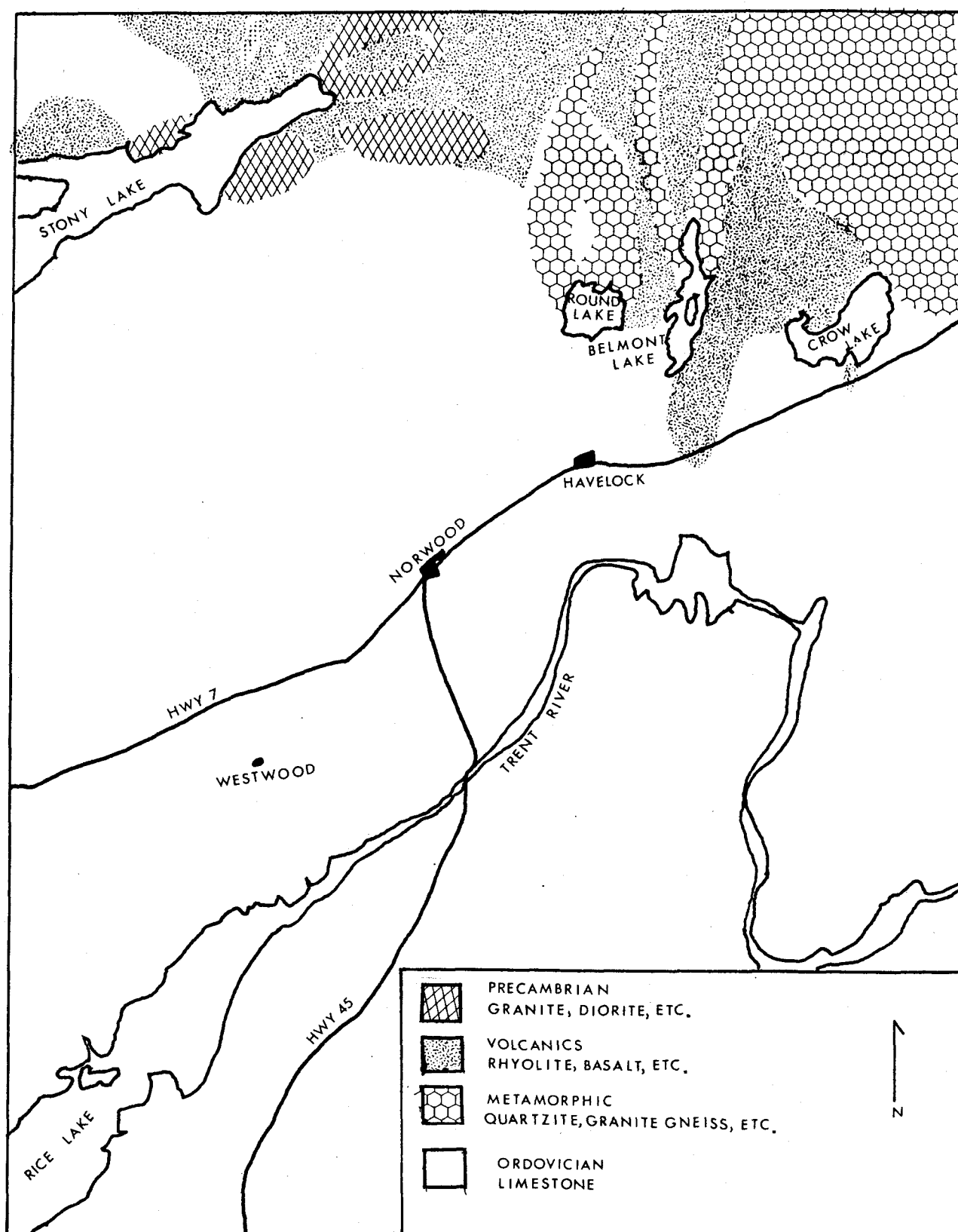


Fig.2-Bedrock geology of the Norwood area (after Hewitt, 1969).



## CHAPTER II

### MORPHOLOGY OF THE NORWOOD ESKER AND SURROUNDING AREA

#### 2.1. Morphology of the Surrounding Area

The area around the Norwood esker can be divided into two morphologically distinct sections, one north and one south of the town of Norwood.

##### 2.1.1. NORTHERN SECTION

The northern section consists predominantly of low marshland that is dotted with conical and elongated kame deposits. These features are usually low, no higher than 10m. above the rest of the area. However, there are two conical kames, both adjacent to the esker, which are about 25m. above the surrounding land surface.

Portions of the area which are neither kame nor marsh are very rocky, consisting of a sandy till strewn with boulders of varying sizes. These boulders are all of local origin and are predominantly sedimentary. Crystalline boulders having an origin just north of Havelock(fig.2).

Because of the relatively low nature of the surrounding area, the esker is easily distinguished from other deposits on the aerial photographs, topographic maps and in the field.

#### 2.1.2. SOUTHERN SECTION

The southern section is quite different from the north, consisting of elongated drumlins that are bounded by low, often marshy, land. These drumlins are so elongated in nature that it is often difficult to identify the esker on the aerial photographs and on the topographic maps. In the field it is even more difficult to discern drumlin from esker, unless one has been following the esker from its source, making air-photo analysis a necessity.

Internally, the drumlins consist mainly of till which, like that of the north, is sandy (Gravenor 1957,

p.14). The southern till however, has a much lower percentage of coarse gravel and boulders. Drumlins of sand and gravel are also present, but these make up only a small percentage of those exposed by road cuts. It must be noted here that the author did not sample the till in the southern section and is therefore only commenting on visual impressions drawn from a number of road cuts in the area. The lower boulder content of the till in the southern section is also implied from the smaller size and lower number of rock piles in the fields and by the fact that most farms in the northern section were raising beef cattle while in the south crop cultivation was taking place.

## 2.2. Morphology of the Norwood Esker

Just as the surrounding area can be divided into two sections, so can the esker itself. It too is different morphologically north and south of the town of Norwood; the northern section consists of a complex series of single and multiple ridge sections, whereas the southern is usually a single ridge.

### 2.2.1. NORTHERN SECTION

The main ridge of the Norwood esker begins to the north east of the town of Havelock. Initial sections of the ridge consist of low, short segments; these segments range from 3 to 9m. in height, 3m. to 12m. in width, and 10m. to 1km. in length. At the north central boundary of Havelock, the ridge becomes multiple, each ridge being 9m. in height and 30m. in width with steep sides and a rounded top. These continue until the esker is crossed by Plato Creek where it again becomes segmented. From this point for a distance of 1km., the esker consists of short segments that have not been eroded by Plato Creek. These show the trend of the esker but appear much like small kames.

To the west of Plato Creek the ridge appears again, now consisting of a low wide, plateau-like base with a higher, steep-sided, single ridge superimposed upon it. The basal section is initially about 20m. wide and 9m. in height but it quickly widens to 1km., retaining the same relative height. The steep-sided ridge on top of the base is about 10-15m. in width and 9-10m. above the top of the basal section. The first of three tributary portions of the esker joins the main

ridge at a point 1km. from the beginning of this two-tiered section.

The tributary esker begins just to the south of Rush Point. It is relatively low and narrow, ranging from 3-9m. in elevation and 10-15m. in width. The esker is quite sinuous over its 4.5km. length and in three places splits into two separate ridges that rejoin about 100m. downstream.

The tributary esker becomes two-tiered immediately upstream of the point at which it joins the main ridge; here too the basal section is low (9m.) and wide (100m.) with a higher, steep-sided, single ridge superimposed (9m.).

From a point just west of the junction of the tributary and the main ridge, to the western limit of the town of Norwood, the esker consists of a low, wide, basal section with from one to six ridges on top of it. Most of the ridges in this multi-ridge section are from 3-5m. above the top of the basal section, while the main ridge is from 6-9m. above the basal section (fig.3).

At a point 3km. east of Norwood a second tributary esker starts and joins the main ridge. The tributary is located on top of the basal section and to the north of the main ridge. It is quite different

Fig. 3-Multi-ridge section near Norwood. The main ridge is on the extreme right; sites 2&3 are to the rear of the trees on the left. The lack of soil or till on the ridge is indicated by the exposed gravel in the foreground and at the base of the tower.

from any of the other tributaries, being short, 700m. in length, about 10m. in height and about 100m. in width with sloping sides and a wide flat top, much more like a second level plateau than a ridge of the esker. Where it joins the main ridge system its surficial morphology changes and it too takes on the steep sides and narrow inverted V-shaped cross section of the main and lower multiple ridges.

From the point at which the second tributary begins to the end of the northern section, the main ridge occupies a position on the extreme southern edge of the plateau-like basal section, giving the esker an elevation of about 20m. above the surrounding terrain. Both sides of the main ridge are steep, the north slope being flanked by one to three lower ridges.

At about the eastern limit of Norwood, the Ouse River has cut a gap through the esker. Here the north slope becomes less steep and is marked with meander scars that indicate past positions of the river. The south slope of the ridge remains steep.

To the west of the Ouse River the ridge rises slowly to the height it had attained before breaching by the river. This gives the ridge the appearance of the slip face of a point bar, possibly indicating that final erosion of the Ouse River occurred from west to east.

The water of the Ouse River flows just south of the esker from here to the distal end where it debouches into Rice Lake. The presence of the river has undoubtedly caused the southern slope of the main ridge to become less steep than sections east of the Ouse River gap; the overall height of the ridge however, remains the same. The northern side of the ridge becomes narrower to the west of the Ouse River gap, here consisting of only two ridges, the main ridge and a less steep ridge to the north. A number of kettle holes are also present in the ridge to the north and the plateau-like base has all but disappeared.

At a point about 300m. from the southwestern limit of Norwood a tributary of the Ouse crosses the ridge causing yet another gap and it is at this point that the morphology of the ridge and the surrounding area change.

#### 2.2.2. SOUTHERN SECTION

The southern section of the Norwood esker is quite different from the northern; although it begins as a double ridge there is no longer a plateau-like base. Meander scars are present on the north facing end of the ridge marking the final position of the Ouse



tributary. The main ridge here is high (25m.) with steep sides. The second ridge, on the northern side of the main ridge, is lower (12m.) and slightly wider, terminating about 1km. downstream.

For the remainder of its length the esker consists of a single ridge (fig.4) although there is a point just east of Westwood at which it splits into two ridges that rejoin about 1km downstream.

At a point marked by Westwood, the West Ouse River crosses the main ridge causing the final sequence of gaps. These segments are of such a shape and frequency that, in the field, they are almost impossible to distinguish from the surrounding drumlins. Also, the third tributary esker joins the main ridge at this point adding to the confusion when attempting to determine the trend of segments and their affiliation to the main ridge or tributary. Close examination of the air-photos for the area however, provides information for identification of the esker segments because of their close association and similar trend to enclosed portions of the main ridge or tributary.

The third tributary is approximately 15km. in length and has its beginning just to the south of Rotten Lake. At this point it is low (3m.), narrow

Fig. 4-Downstream view of the ridge at the start of the southern section. Note the relatively steep side and the single nature of the ridge at this point.

(9m.) and sinuous, yet, in a distance of 2km., it has attained a height of about 9m. and a width of approximately 20m. Past this point the ridge again becomes lower, narrower, and segmented, segmentation being the result of breaching of the ridge by the West Ouse and its numerous short tributaries.

Approximately 6km. from the main ridge the tributary is joined by a short, low tributary. From this point for a distance of about 2km. the ridge is low (3-5m) and wide (20m.) with a rounded top. At a point about 4km. from the main ridge the tributary splits forming two ridges, each of which is segmented by the West Ouse River. The southern section of the split joins the main ridge just east of Westwood, while the northern section joins the main ridge just to the west of Westwood.

From the point of junction to the shore of Rice Lake, the ridge becomes increasingly higher (60m.) and wider (2km.) until it takes on the appearance of the surrounding drumlins and may be the result of basal flow, much like sheet flow. This condition likely occurs from large amounts of melt in an easily eroded and highly porous ice mass. The end of the ridge slopes steeply to the shore of Rice Lake with an area of flat land about 200m. from the base of the slope to

the shore. This high wedge shaped section of the ridge has a number of steps on the east side, indicating either the position of meltwater streams or the shore of glacial Rice Lake which Gravenor (1957), Chapman and Putnam (1966, p.34), and Hewitt (1969, p.13) have suggested occupied this area.

### 2.3. Explanation of the Surface Morphology

#### 2.3.1 THE SURROUNDING AREA

The landforms present in the area around Norwood are indicative of a warm stagnant or ablating ice mass. Cold ice would not melt to any extent, eliminating the amount of water and sediment necessary for esker and kame deposits of the size and extent of those found within the study area. Also, moving ice would eradicate any features deposited during a warm period. The necessity of stagnant or ablating ice for the formation of these types of deposits has been suggested by Flint (1930), Shaw (1972), Banerjee and McDonald (1975), and Saunderson (1977b).

The difference in the morphology between the northern and southern sections of the area may be due to two related factors.

First, there may have been a difference in the thickness of the overlying ice in the two areas. The north may have been covered by a thicker body of ice that contained a number of crevasses and ice confined lakes. During periods of high melt, these may have become filled with water and sediment. As the amount of fluid increased the hydrostatic pressure within specific areas of the ice also increased to a point at which one or more of the crevasses may have been expanded or new channels formed at weak areas within the ice. As the size of these fissures increased, water and sediment moved into them increasing pressure until it was released either by the bursting of an ice dam or through the breakthrough of a crevasse or tunnel to the ground or the snout of the glacier. If the ground were reached then the water may escape by spreading beneath the glacier, leaving behind a mass of poorly stratified to unstratified material that might become kame. If it broke through the snout or sidewall of the glacier, jokulhlaup flow could occur quickly releasing the hydrostatic pressure and reducing the amount of water within the channel. Deposits formed in this manner might well resemble esker deposits.

The closure of the tunnel or channel may or may not take place depending on the amount of water

available and on the pressure of the surrounding ice. Rothlisberger (1972) discussed the development and durability of such channels in Sweden. He found that both conditions occur, and suggested hypothetical pressures required to create and maintain subglacial tunnels. The close association of the kame deposits and the esker suggests that they may have been linked as part of a system of subglacial channels that were utilized during high periods of melt.

The southern section may then have been covered by a less thick, warmer and wetter ice mass in which water moved freely from the surface through to the base of the ice mass and then out to the snout in a type of basal sheet flow. This would explain the elongated shape of the drumlins and the incorporation of the esker and drumlin field at the distal end of the esker.

The overall warmth and ease of water movement may have resulted in the development of elongated cavities within the ice, possibly in areas of weakness. These in turn may have been filled from above with detritus that, when finally exposed, takes on the shape of drumlins.

### 2.3.2. MORPHOLOGY OF THE ESKER

The morphology of the Norwood esker may differ from north to south for exactly the same reasons as the morphology of the surrounding area.

In the north, the thicker ice required large amounts of water and great hydrostatic pressures to initiate englacial or subglacial channels. Once formed, these may have been kept open by sufficient supplies of meltwater because they were the only channels available to remove water and sediment from the warm, moist surface area. Rothlisberger (1972), indicated that, once formed, conduits (tunnels) rapidly increase in size (days) and close more slowly (months-years), suggesting that only small amounts of water and sediment would be needed to sustain pipe or tunnel flow. He also noted that subglacial water migrates down pressure gradients toward main flow, and that the conduits may be straight, meandering, or even braided depending on the hydraulic gradient; this explains in part, the size, extent and shape of the Norwood esker complex. Shreve (1972) noted that the stable mode of subglacial water movement is in tunnels and that the subglacial formation of eskers is favoured by large discharge and low glacier surface gradients.

The point at which the two-tiered, plateau-like section begins may mark a position at which basal flow moved outward in a softer portion of the ice, with the upper section of the plateau marking the position of the ice roof.

Multiple ridge sections may be either a reflection of the shape of the ice roof or the result of collapse due to the melting of ice cores, or the combination of both of these factors. Howarth (1971) indicated that multiple ridges in the eskers at the snout of the Breidamerkurjökull glacier are the result of ice cores within the deposit that melt after deposition. The author feels that the multiple ridge sections of the Norwood esker are the result of two factors, 1) the ice roof and 2) the melting of internal ice. The reasons for this hypothesis are that a) where multiple, the main ridge is invariably higher and on the south side of the complex, b) multiple sections are not always parallel to the main ridge, and c) high angle reverse faulting is present in some of the sections but displacement of material is not great and does not include the entire sediment column exposed.

The fact that the main ridge is always highest, indicates that it was the preferred channel and therefore carried most of the sediment and water.



Other ridges do not always parallel the main ridge, suggesting that although they have a common base, at upper elevations, sections of the tunnel were separated by perhaps more resistant ice, forcing water and sediment to take a somewhat different course than that in the main channel. After deposition, ice cores within the ridge system melted causing minor ridges on the contemporaneous plateau-like base(fig.3). This may also explain the short areas of bifurcation which occur throughout the length of the entire esker complex for these may also mark the position of more resistant ice.

Southern sections of the esker may mark the position of a soft ice mass that was easily incorporated into the system of englacial or subglacial channels. The width, height and relative straightness of the Southern ridge may well indicate the softness and erodibility of the ice in this area. Also, the fact that the distal end of the esker expands in area and height, to such an extent that it appears part of the drumlin field, adds weight to the hypothesis that southern sections were wetter with almost total basal flow.

### CHAPTER III

#### ANATOMY OF THE NORWOOD ESKER.

##### 3.1. Location and Description of Sample Sites

Internal structures of the Norwood esker were examined and sampled at eleven sites over the length of the esker. Other sites were visited but not sampled because the sediments were similar to those found at main sites or the sites had been disused for so long that sampling was impossible. Sites 1-7 are located in what has been referred to as the northern section of the esker, while sites 8-11 are located in the southern section (fig.1). In actual fact the sites are distributed over the entire length of the esker complex providing insight into the sediments below complex morphological features.

Site 1 is located in the double ridge portion of the main ridge on the western limit of Havelock. Here the esker consists of a core of matrix-supported gravels with flanking sections containing cross-bedded sands and gravels as well as some fine sands and silt (figs. 5,6).

Site 2 is located in the middle of the low, wide ridge of the second tributary, just north east of Norwood. It consists of an upper section of matrix-supported gravels and sands with lower sections containing mainly cross-bedded sands and gravels, and cross-laminae of fine sands.

Site 3 is located 200m. south east of site 2 at the point where the second tributary meets a minor ridge of the main system. This site is made up of two separate sections. The rear section consists of cross-laminae and cross-beds of sand and the front cross-bedded sands and gravels overlain by matrix-supported gravels and sands (figs. 7,8,9,10). This site also contained a bed of large cobbles that occupied a basal position in the middle of the pit, as well as a layer of angular fine gravel in high stratigraphic position (figs. 11,12). These somewhat anomalous deposits indicate deposition under very special conditions.

Site 4 is located approximately 500m. downstream from site 3 in the same minor ridge. It too consisted of the matrix-supported gravels underlain by cross-bedded sands and gravels.

Site 5 is located on the south side of the main ridge at approximately the eastern limit of Norwood. It consists of an upper and middle, horizontal layer of matrix-supported gravels and sands, separated, and underlain by cross-bedded sands and gravels and flanked by sands.

Site 6 is located to the north of the main ridge at Norwood. It consists of alternate, parallel layers of sand and granule gravel (fig. 14).

Site 7 is located in the end of the esker at the western limit of Norwood where the tributary of the Ouse crosses the ridge. The esker here is high, upper and middle layers being matrix-supported gravels and sands with cross-bedded sands below and between, like those at site 5. The lower ridge to the north is primarily cross-bedded sands and gravels, upper sections consisting of finer matrix-supported gravels and sands and flanked by sands (figs. 15,16).

Site 8 is located on the south flank of the main ridge approximately 1km. east of Westwood. It consists of parallel layers of sand and granule gravels similar to those found at site 6.

Site 9 is located in the third tributary, just south of hwy.7. The ridge here is low and wide, internally consisting of an upper layer of matrix-supported sands and gravels with lower layers of alternating sands and granule gravels.

Site 10 is located about 1km. west of Westwood, at a point where the main ridge and the third tributary join. This site is quite different from any other, the upper 15-20m. consisting of fine sands and silts, lower sections being primarily cross-bedded sands and gravels with some cobble and boulder gravel present at basal positions (figs. 17,18,19).

Site 11 is located in the upper section of the distal end of the esker. It consists of upper layers of massive sands and gravels and lower layers of cross-bedded sands and gravels.

### 3.2. Description of Facies

The sediments contained within the Norwood esker can be grouped into a number of facies types based on particle size and the primary sedimentary structures present at the sampling sites.

Particle sizes found within the esker ranged from boulder gravel to silt and were found within a

wide range of primary sedimentary structures from both the upper and lower flow regimes. The facies types and their characteristics are summarized in table 1.

### 3.2.1. COARSE GRAINED FACIES A-E.

Facies A consists of massive, poorly sorted, gravels and sands in which cobbles and other large clasts were surrounded by finer gravels and sands, similar to those described by Saunderson (1977b). In the northern section of the esker upper sections of most sites consist of this facies.

Facies B, consisted of clast supported gravels with some sand and silt present. Deposits of this facies often appeared as openwork gravel and were located in association with cross-bedded gravels and sands and cut and fill.

Facies C, consists of cross-bedded sands and gravels and was by far the most common facies throughout the esker complex making up well over half the material in the ridge.

Facies D, consists of massive gravels and sands. These deposits were likely formed on the face of gravel bars and during rapid sedimentation of sizes from cobble to fine sand at high flow velocities. They

differ from facies A in that the cobbles are of smaller size and no boulders are present.

Facies E, consists of granule gravel and was present in areas of cut-and-fill as well as alternate layers between ripple or parallel-laminated sand and silt. This facies was often located on the flanks of the esker and in upper sections of more southerly sites.

### 3.2.2. FINE GRAINED FACIES F-H.

Facies F, consists of ripple laminated fine sands and silts. The ripples were consistently of types A and B described by Jopling and Walker (1968), and were most commonly found in flank positions of the esker in the northern section and in upper and flank positions in the south.

Facies G, consists of parallel laminations of fine sands and silts and occupied a position above facies F. This facies also was located primarily on the flanks.

Facies H, consists of fine sands and silts with convoluted filaments of silt or clay. This facies was only encountered in site 7, but may well be present in other sections of the ridge that are either covered with scree or have not yet been excavated.

TABLE 1: Generalization of Facies types.

FACIES TYPE	GRAIN SIZE RANGE	PRIMARY SEDIMENTARY STRUCTURE	INTERPRETATION OF ORIGIN
A	$\geq -6.50 \phi$ pebble to clay sizes	massive	sliding bed during full pipe flow.
B	$-5.50\phi - -3.75\phi$ some sand and silt	openwork	special flow velocity with rapid burial.
C	all sizes	cross-bedding	high velocity flow with high occurrence of cut and fill.
D	$< -6.50\phi$ all sizes from gravel to clay	massive	high flow vel- ocity with all sizes in motion.
E	$< -2.50\phi$	plane bed	laid down just at the end of upper flow regime with rapid burial by the succeeding fines.
F	$< -1.00\phi$	ripple laminated fine sand and silt	lower flow regime with high concen- tration of suspended load.

$\phi$  is equal to  $-\log_2 m$  where  $m$  is the size in millimeters.



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G	< -1.00ø	parallel laminated sands	upper flow regime plane bed, high concentration of suspended load.
H	< +1.50ø	massive with convolute structure	fluid drag at high flow velocity, high concentration of suspended load.

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### 3.3. Facies Associations

The sample sites used in this study are located in such a manner that they provide a good indication of the anatomy of the ridge, both transversely and longitudinally. This in turn permits fairly reliable interpretations to be made on the conditions of flow present at the time of deposition. Sites 1-7 represent the northern section and sites 8-11, provide information on the southern section.

#### 3.3.1. TRANSVERSE DISTRIBUTION OF FACIES

Site 1, located at Havelock, contains a central core of very coarse, matrix-supported boulder and cobble gravel (fig.5), some of the boulders having a B-axis of about 73cm. This coarse core is overlain by layers of finer matrix-supported gravels and is flanked by cross beds of sands and gravels (fig.6).

The position of these coarse matrix-supported gravels suggests initial deposition took place within a pipe, or tunnel, flowing full (Saunderson, 1977b). Final stages of flow were similar to open channel flow



Fig. 5-Matrix-supported deposit at the core of site 1; upper sections seem to be finer and dip at a low angle downcurrent suggesting deposition over the face of a bar or delta. The shovel, just below the tower, is 63cm long.



Fig. 6-Sub-angular openwork gravel bounded above and below by matrix-supported gravels and sands. This deposit occupied a position near the top of site 1. The scale in the photo is a Canadian quarter.

and occurred on the flanks as indicated by the presence of the cross-bedded sands and gravels. (A more detailed discussion of the rationale behind suggested flow conditions will be given in section 3.6. of this chapter.)

Site 2, located in the second tributary, consists of an upper layer of matrix-supported gravels and sands similar to those found at site 1 but considerably finer grained, maximum B-axis being 13cm. The core of the ridge at this point consists of cosets of dunes and cut-and-fill features, with approximately 80% of the sediments in the sand and granule gravel range. The cross-bedded features suggest that the major portion of the sediments were in a pipe or tunnel flowing full of water but at low flow discharge, or in a pipe or tunnel that was only partially full of water similar to open channel flow. The presence of the dunes and cut-and-fill structures suggest that deposition occurred in either the upper portion of the lower flow regime as described by Simons, Richardson, and Nordin (1965) for open channels or lower flow velocities for pipes as described by Acaroglu and Graf(1968), and McDonald and Vincent(1972). The presence of the matrix-supported gravels at the top of the deposit suggests a final reworking of the upper

portions of the esker during full-pipe flow with waning flow on the flanks depositing the ripple laminated sands and silts.

Site 3, located at the junction of the second tributary and the minor ridge represents two very different flow conditions. The sediments at the rear of site 3 consist of cross-beds and cross-laminae of sands (figs.7,8,9). These suggest deposition within the lower flow regime, lowest layers likely in deep water, minimum flow depth being 3m. because of the thickness of the cross-bedded set. The front section of the site is made up of steeply sloping cross-bedded gravels and sands interfingering with and overlain by festoons of cross-bedded sands and cut-and-fill features. Superimposed on these are matrix-supported gravels and sands of the same type found in site 2 (fig.10). The lower portion of the deposit suggests that a longitudinal bar may have been present at this location, the angle of the cross-beds indicating flow separation to the lee of a bar or delta-like deposit. The entrance of the tributary has cut into this deposit (cut-and-fill) and has also been incorporated into it (fig.10).

The presence of a layer of boulder gravel at the base of the deposit (fig.11) suggests extremely high flow conditions in either an open or closed channel.



Fig. 7-Upper rear of site 3; pseudo-cross-bedding near the shovel and upper portions of the site suggest flow from left to right, but these are actually boundaries of climbing ripples and flow was from right to left.

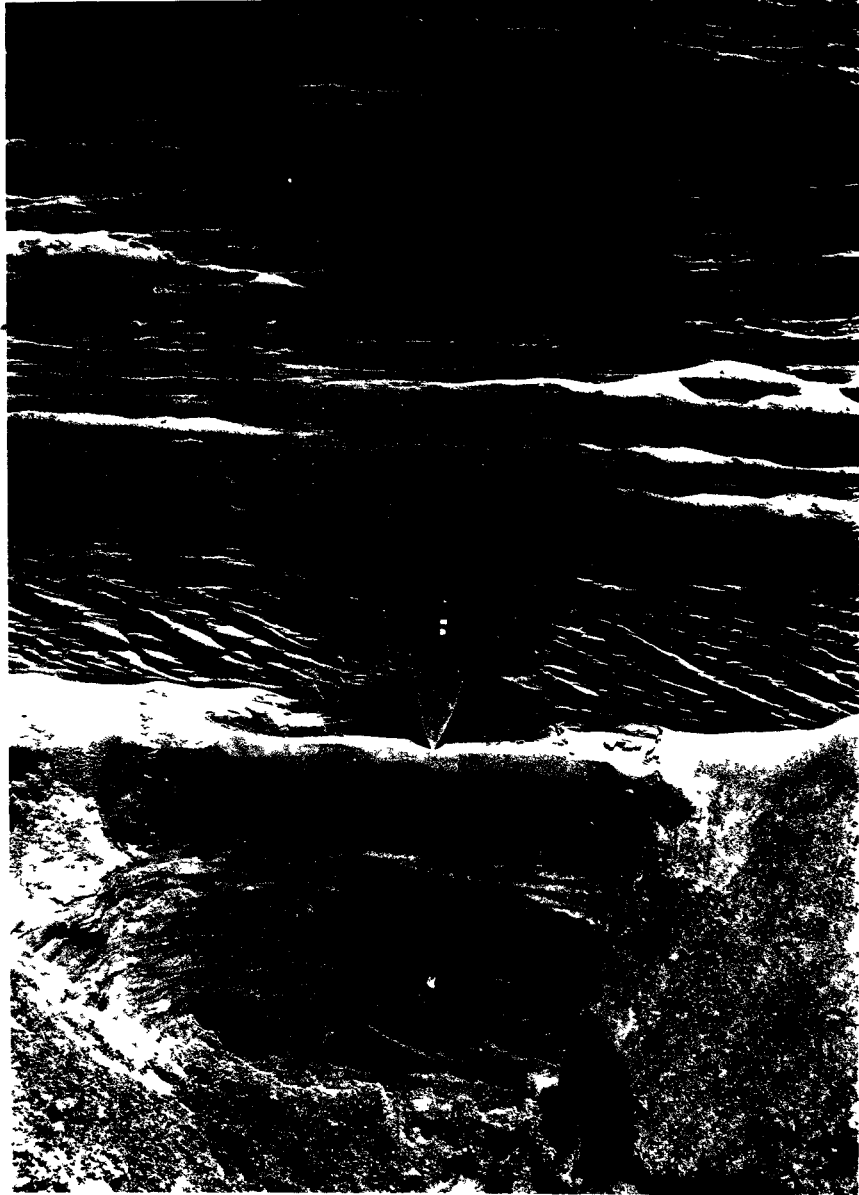


Fig. 8-Close-up of the rear of site 3. Again note the pseudo-cross-beds and the actual flow direction within the cleared section. The top of the trowel is resting on parallel laminae likely produced during upper flow regime. The sequence of ripple-laminae below the trowel also indicates transition from lower to upper flow regime, with high concentrations of suspended load. The trowel is 30cm. long.



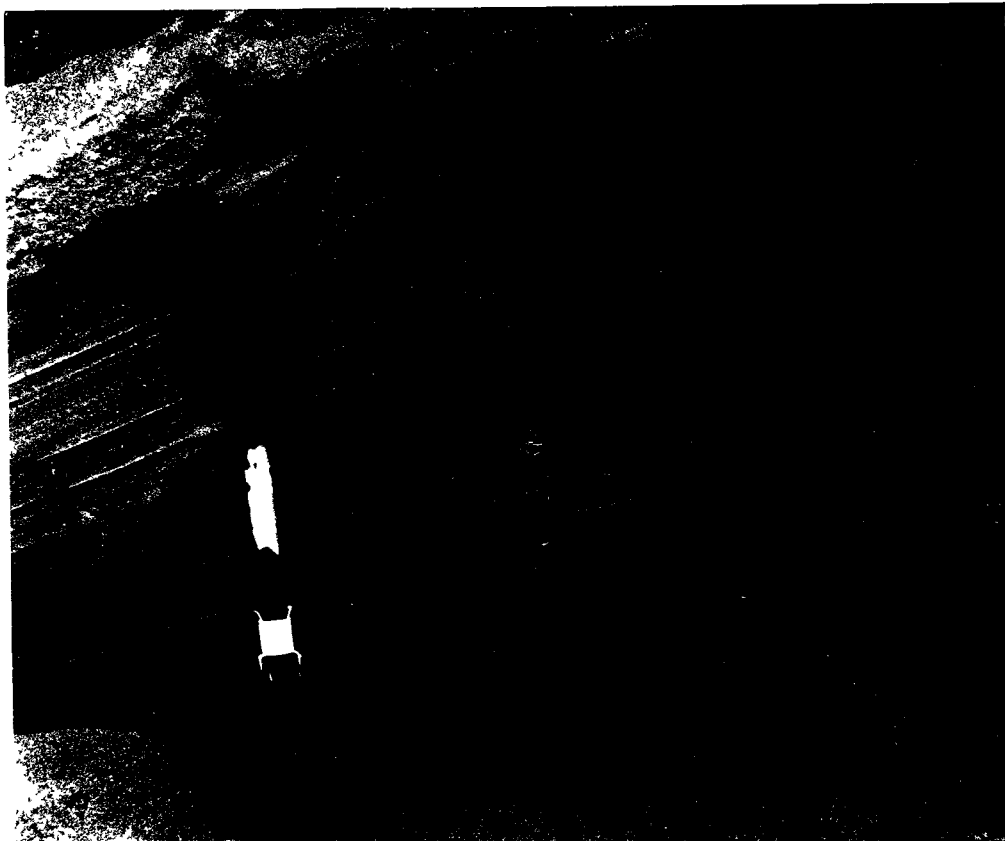


Fig. 9-Low angle cross-beds of sand at the lower rear of site 3, indicating deposition in deeper water because of the thickness of cross-bedded set. This photo is a close-up of an exposure that has a depth of 3m.



Fig. 10-Front section of site 3; upper portion is matrix-supported gravels and sands, lower sections are cross-bedded gravels and sands, with middle portions consisting of cut and fill.

Near the top of the section a layer of angular gravel is present (fig.12). The presence of the angular gravel, especially limestone, is abnormal in a fluvial deposit. Sneed and Folk (1958) indicate that limestone reaches its maximum roundness in a distance of from 5-15km. These sediments obviously must have been crushed nearby and then rapidly deposited and buried.

The fine sand at the rear of the site is deposited in low angled cross-beds at low stratigraphic position, the thickness of the cross-bedded set indicating entrance into deeper standing water (fig.9) while upper stratigraphic sections (fig.7,8) have been laid down at a time when large amounts of sediment have been available for deposition as indicated by the festoons of climbing ripples.

Site 4, located approximately 500m. downstream from site 3 contains similar structures to the front portion of site 3. Lower sections of this site are made up of cross-bedded sands and gravels overlain in upper sections by matrix-supported gravels and sands. Here, dunes and bars are the dominant bedforms. The position of the matrix-supported deposit indicates a final episode of full-pipe flow.



Fig. 11-Layer of boulder and cobble gravel at the lower right of site 3. These indicate high flow velocity in an open or closed channel.



Fig. 12-Angular granule gravel of limestone, indicating local crushing and rapid burial. The rounded pebble gravel has been transported greater distances.

Site 5, located on the south side of the main ridge approximately 2km. downstream from site 4, consists of an upper and middle layer of matrix-supported gravels and sands below each of which are cross-bedded sands and gravels (fig.13), suggesting two periods of full-pipe flow separated by periods of lower flow velocities or lower flow depths or both.

Site 6, located in the northwestern section of the lower ridge about 2km. down stream from site 5, is very different from sections previously described. It consists of parallel layers of sands separated by alternating layers of granule gravel (fig.14). The sand layers represent deposition during lower flow regime, while the granule deposits may mark erosional boundaries, deposition occurring at the end of upper flow regime with rapid burial by the subsequent sand layers (Harms and Fahnestock 1965, p94).

Site 7, located at the end of the north section of the esker, gives a representative cross-section of the entire esker complex at this point. The main ridge deposits are the same as those of site 5 with a similar distribution of sediments. The lower ridge to the north is made up of a core of coarse gravels and sands overlain by a matrix-supported deposit (fig.15). Just down stream of this section the deposit is similar to



Fig. 13-Site 5, upper and middle sections are matrix-supported sands and gravels; all other portions are cross-bedded sands and gravels.

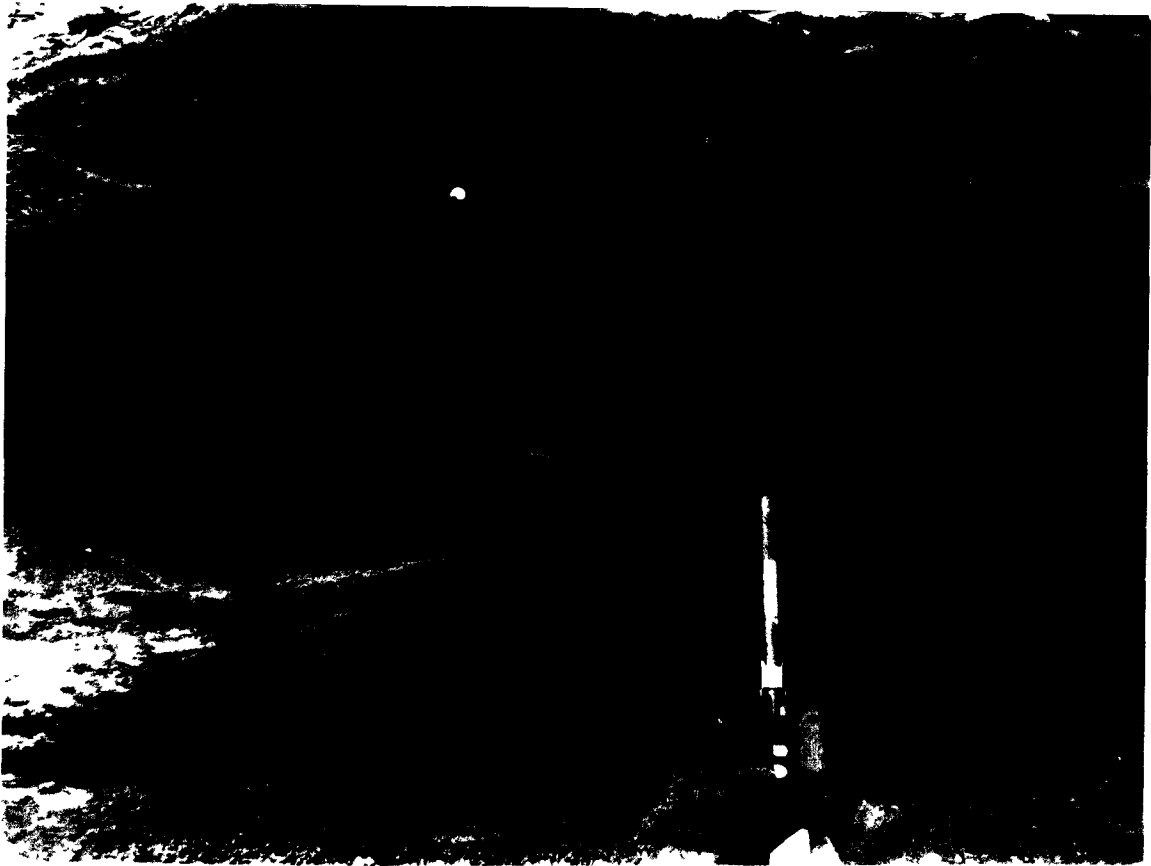


Fig. 14-Site 6, alternating layers of sand and granule gravel may indicate periods of fluctuating flow velocity. A micro-delta is present at the base of the shovel, flow was from right to left.



that of site 6, with alternating layers of sands and granule gravel (fig.16).

One of the sand layers contains convoluted structures of clay that are likely the result of fluid drag over thin layers of clay deposited at low flow. The force of the drag draws the clay up into the suspended sediment but the plasticity of the clay, combined with rapid sedimentation of the sand, prevents it from being removed from the bed and it is incorporated into the deposit as a type of flame structure.

Site 8, located on the south side of the main ridge about 1km.east of Westwood, consists of alternating layers of sand and granule gravels with some lower sections containing cross-bedded sands. Upper sections were consistently of sand and silt sizes.

Site 9, located in the third tributary just south of hwy.7, consists of parallel layers of sand alternating with granule gravel. These were overlain by massive sands and gravels of the matrix-supported type, indicating that again final deposition occurred in a pipe or tunnel flowing full of water.

Site 10, located just west of Westwood at a point where the main ridge and the third tributary

Fig. 15-Northern section of site 7; upper portion is matrix-supported gravels and sands, central is massive to cross-bedded gravels and sands. The cross-section appears somewhat like a bar or dune structure.

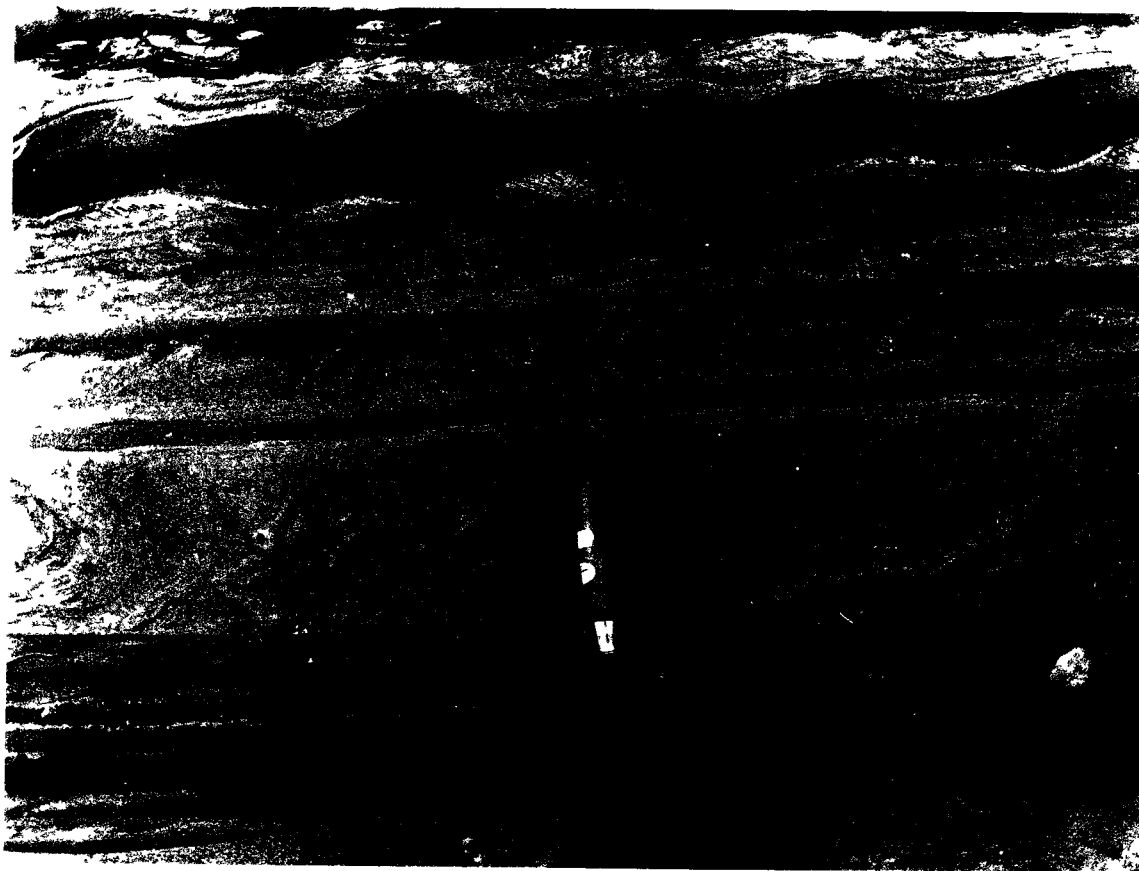


Fig. 16-Site 7 just downstream from Fig.15; the granule layer at the middle of the trowel may mark an erosional contact. The convolute structure, marked by the trowel handle, is of the fluid drag type and was only encountered at this site.

join, consists of a large upper layer (15-20m.) of sands and silts underlain and interfingering with cross-bedded layers of sands and gravels (fig.17). These suggest the deposition of a central core of sands and gravels over the surface of a longitudinal bar or delta, with final layers of sand being deposited as flow waned (fig.18,19).

Site 11, located approximately 6km. downstream from site 10, consists of layers of parallel-bedded sands and gravels that are overlain by a layer of massive sands and gravels. This deposit appears more like outwash, with channels marking flow in what may have been a braided environment within a tunnel that was only partly full or as a result of basal sheet flow.

Over the length of the esker, the facies tend to change from being coarse to finer grained as one moves for the proximal to the distal end. Facies also tend to be finer grained on the flanks, likely because waning flow occurred there rather than remaining on the top of the higher central core.



Fig. 17-Site 10; note the high concentrations of sand in upper sections of the exposure and the interfingering with the central gravels and sands. This indicates contemporaneous deposition as flow velocities decreased.



Fig. 18-Rear of site 10; the cross-bedded sands and gravels suggest deposition over the face of a bar or delta. View is downstream into the flow.



Fig. 19-Again the rear of site 10 looking downstream;  
sand on top of the delta or bar indicates  
lower flow velocity.

### 3.4. Particle Size Analysis

The size of particles found within a deposit is of considerable importance to the researcher, because it allows one to make a number of interpretations about the hydraulic origin of the deposit. When related to primary sedimentary structures it can provide information on flow depths, flow velocities, and can be employed to determine the environment of deposition be it aeolian, beach, or river. For example, Friedman (1961) used the summary statistics of grain size to distinguish dune, beach and river sands; whereas Visher (1969) suggested its importance in identifying ancient fluvial environments; on the other hand Landim and Frakes (1968) employed grain size to distinguish tills from other diamictic deposits.

The present study, employs the cumulative frequency distributions in order to describe the deposits. In addition, the summary statistics of Folk and Ward (1957) were calculated and are included in Appendix A.



#### 3.4.1. METHOD OF SAMPLING FOR PARTICLE SIZE ANALYSIS.

Samples were collected at eleven sites over the length of the esker. Individual samples were taken from homogeneous layers as suggested by Otto (1938), in a manner such that the complete body of the deposit was sampled. The concept of facies, based on primary sedimentary structures, greatly facilitated this procedure. Structures sampled included cross-bedding, cross-lamination, and massive bedding.

In obtaining a bulk sample of cross-laminations or cross-bedding a trowel was passed across the face of the deposit at right angles to the bedding, thus rendering a sample that was representative of the entire deposit. Massive beds were sampled in a similar manner. This procedure was repeated until a sample of sufficient size was collected. One hundred grams of sand and at least 2kg. of gravel were collected from respective facies.

When large boulder or cobble clasts were encountered, especially in the matrix-supported gravels and sands, only those sizes which could be sieved were collected, the B-axis of the fifty largest clasts being recorded to represent the larger sizes. The measured sizes could not be graphed with the sieved results but

do provide comparable information on the size of cobbles found at other points within the esker.

At each of the eleven sites a sample was taken from each distinct facies found; in cases where alternate layers of similar sizes were present one sample was taken from each obviously different layer only. In all 56 samples were collected and then analysed.

#### 3.4.2. LABORATORY ANALYSIS OF SIZE DATA.

Each sample was analysed using the method suggested by Folk and Ward (1957). Sand samples were split to between 50-70 gm., while for gravel samples the whole sample was sieved to  $-1.00\phi$  and then the remaining sand was split to 50-70gm. The sediments were placed on the Ro-tap machine for 15 min.; a quarter phi interval was used to maximize accuracy for sizes finer than  $-4.50\phi$  and half phi from  $-6.00\phi$  to  $-4.50\phi$ , quarter phi not being available for these sizes. The results of the sieving were plotted as cumulative frequency distributions on probability paper and the graphical measures of Folk and Ward (1957) were calculated.

### 3.4.3. INTERPRETATION OF CUMULATIVE FREQUENCY CURVES.

It has been noted by a number of authors that grain size distributions tend to be Gaussian or at least approximately Gaussian in distribution. For example, Visher (1969) suggested that cumulative frequency distributions were made up of three Gaussian sub-populations, each representative of a particular mode of transport, traction, saltation, or suspension.

Many authors consider cumulative frequency distributions to be of only one shape; however, it has been the experience of the present author, that there are a number of groups of curves and that the shape of these curves is related to the type of primary sedimentary structure in which it is deposited. For this reason the author has plotted the results from similar types of deposits on the same sheet of graph paper (figs.20-25).

Saunderson (1977a, p.47) has established five categories that he feels represent the groups of curves which are present in cross-bedded, cross-laminated, massive, graded and parallel-laminated sands:

- 1) S-shaped curves
- 2) inverted L-shaped curves
- 3) convex curves

4) plots that are almost perfectly straight

5) multi-modal curves of irregular shape.

These categories only hold as long as one is referring to the sand size range. Figures 20 and 21 show cumulative frequency distributions from sand sized deposits.

The curves on figure 20 are from cross-laminated sands and appear to be almost straight. The straightness is the result of relatively good sorting as shown by the fairly low values of standard deviation (.74 for curve 7-8) and the fact that each of the curves is only slightly skewed, values of skewness ranging from .09 for curve 7-8 to .10 for curve 10-2 indicating an almost normal distribution.

The curves on figure 21 are from parallel-laminated sands. These curves are also quite straight, having similar characteristics to those on figure 20. The similarity of these curves, despite the difference of sedimentary structure in which they are found, underscores the need to know the structure before one can attempt to properly analyse the distribution curves.

The curves on figure 22 are from cross-bedded sands and gravels with only curve 1-2 appearing like the S-shaped distribution Saunderson (1977a) suggests

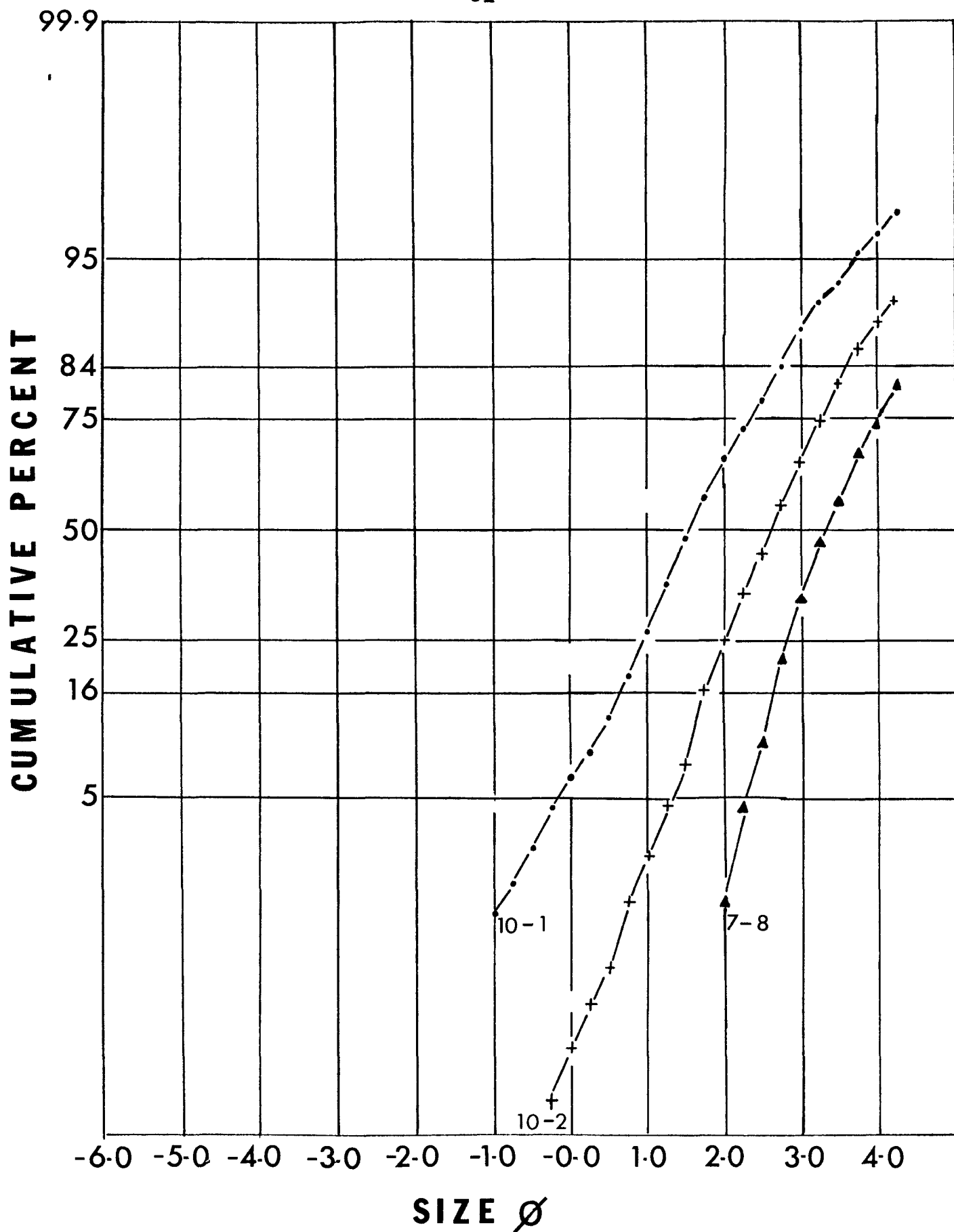


Fig. 20-Selected cumulative frequency distribution curves for cross-laminated sands. Numbers refer to site and sample number respectively. These curves appear almost straight because they are relatively well sorted.

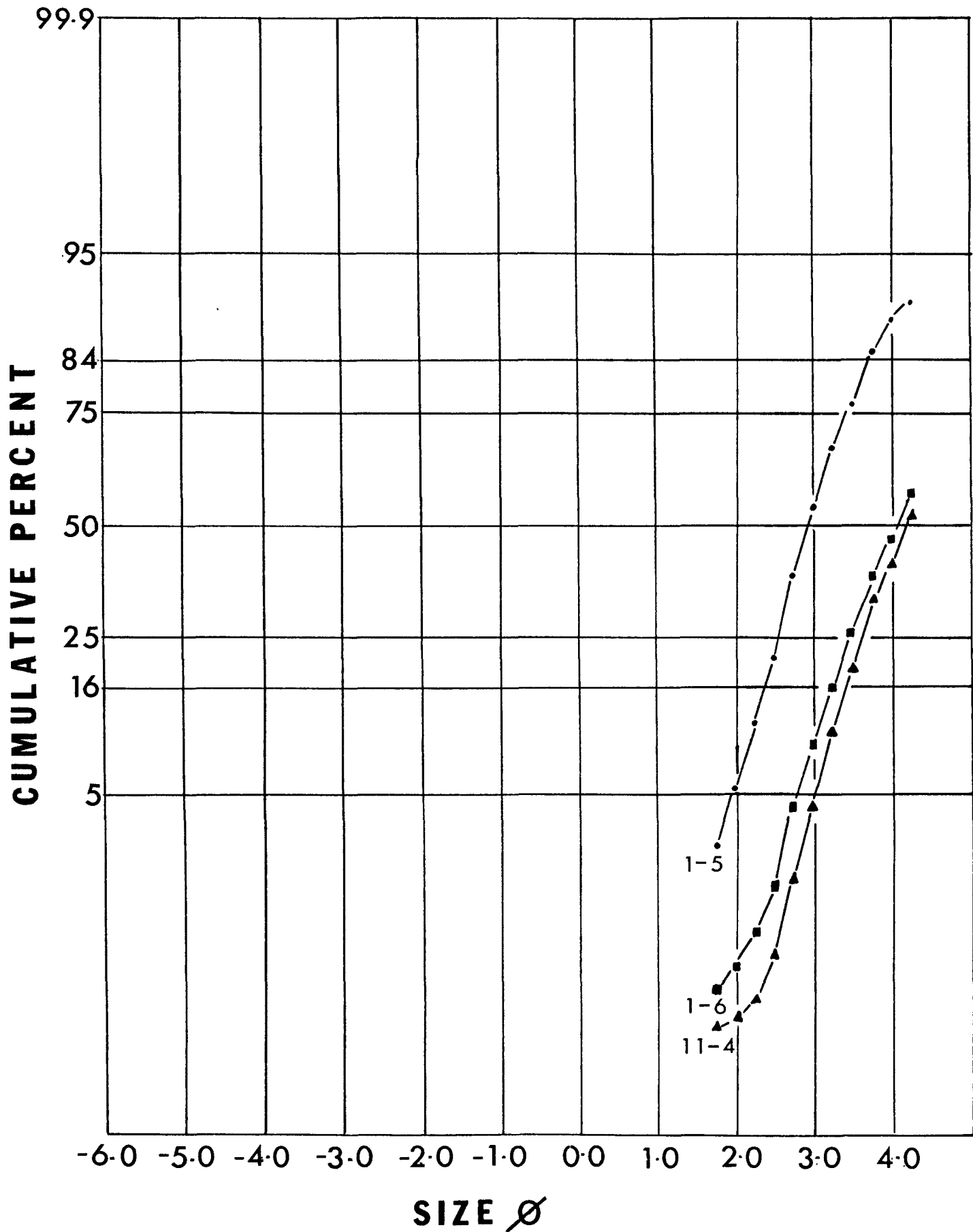


Fig. 21-Selected cumulative frequency distribution curves for parallel-laminated sands. These curves are also quite straight.

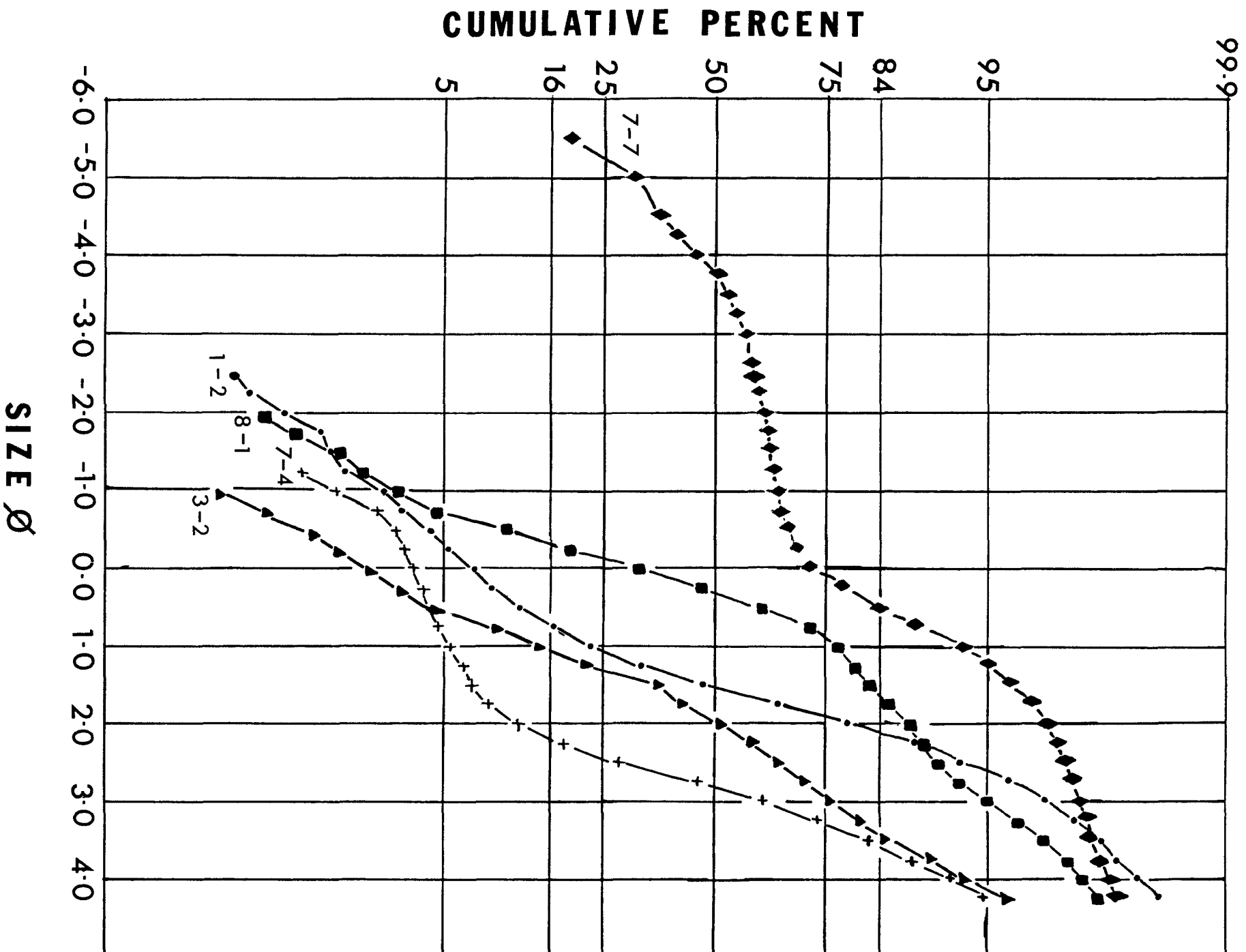


Fig. 22-Selected cumulative frequency distribution curves for cross-bedded sands and gravels. Only curve 1-2 is of the S-shape of Saunderson (1977a). Curve 7-7 is bi-modal.

for cross-bedded sands. Curve 8-1 is from a layer of the granule gravel and coarse sand which occurred so frequently between layers of fine sand. The high percentage of granule gravel is not common in fluvial deposits. Its abundance in the Norwood esker is likely attributable to the high degree of aggradation which occurred here. Curve 7-7 is from large scale cross-bedded gravel and sand and is bi-modal because of the deposition of gravels and sands as alternate foresets in a zone of flow separation. Thus, the presence of gravel within a deposit drastically alters the shape of the distributions described by Saunderson (1977a) for sand sizes.

Openwork gravel (fig. 23) appears as a convex upward curve, the convexity being the result of a deficiency of the sand sizes. This is due to the method of deposition, gravel sizes being deposited first as a clast supported deposit and sand infiltrating the pore spaces as flow velocity decreased. The presence of the sand sizes causes the deposit to appear poorly sorted with a standard deviation of about 1.44 and a skewness of about .29 (for curve 3-5).

Massive gravels and sands (fig.24) and matrix-supported gravels and sands (fig.25) appear



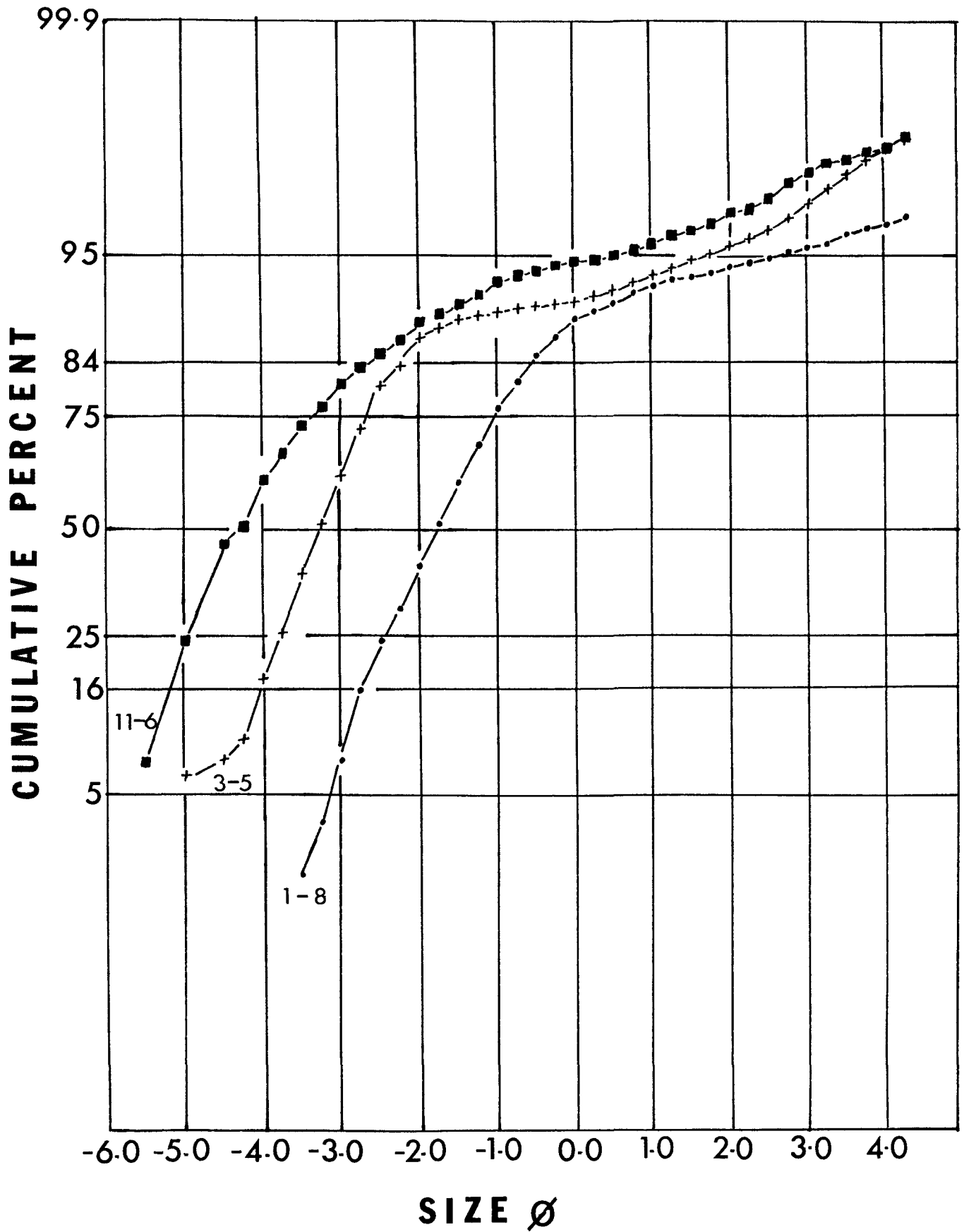


Fig. 23-Selected cumulative frequency distribution curves for openwork gravel. These are formed as clast supported deposits with the sand infiltrating the pore spaces as flow velocity decreases.

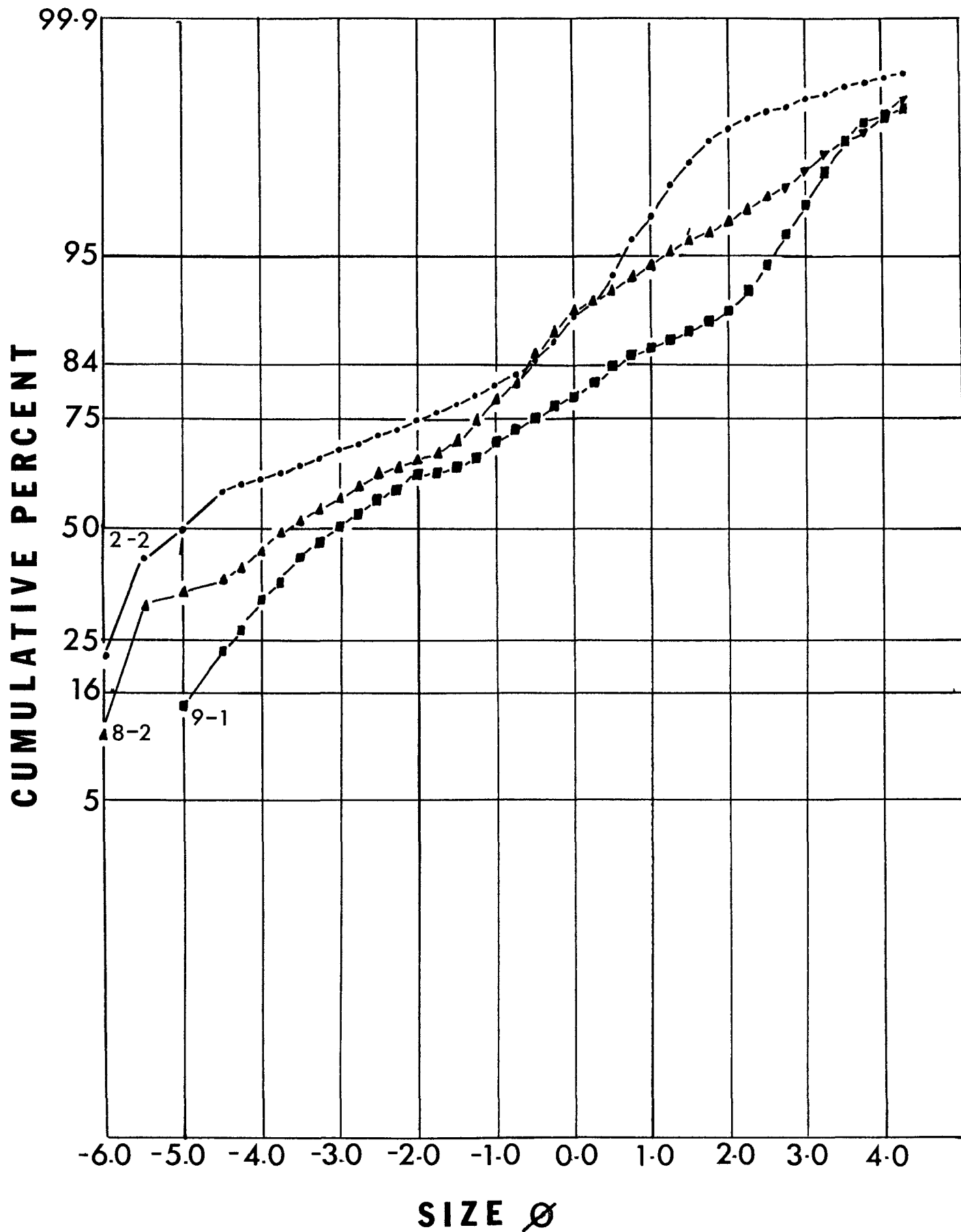


Fig. 24-Selected cumulative frequency distribution curves for massive sand and gravel. These curves indicate that the majority of sizes were in the gravel range.

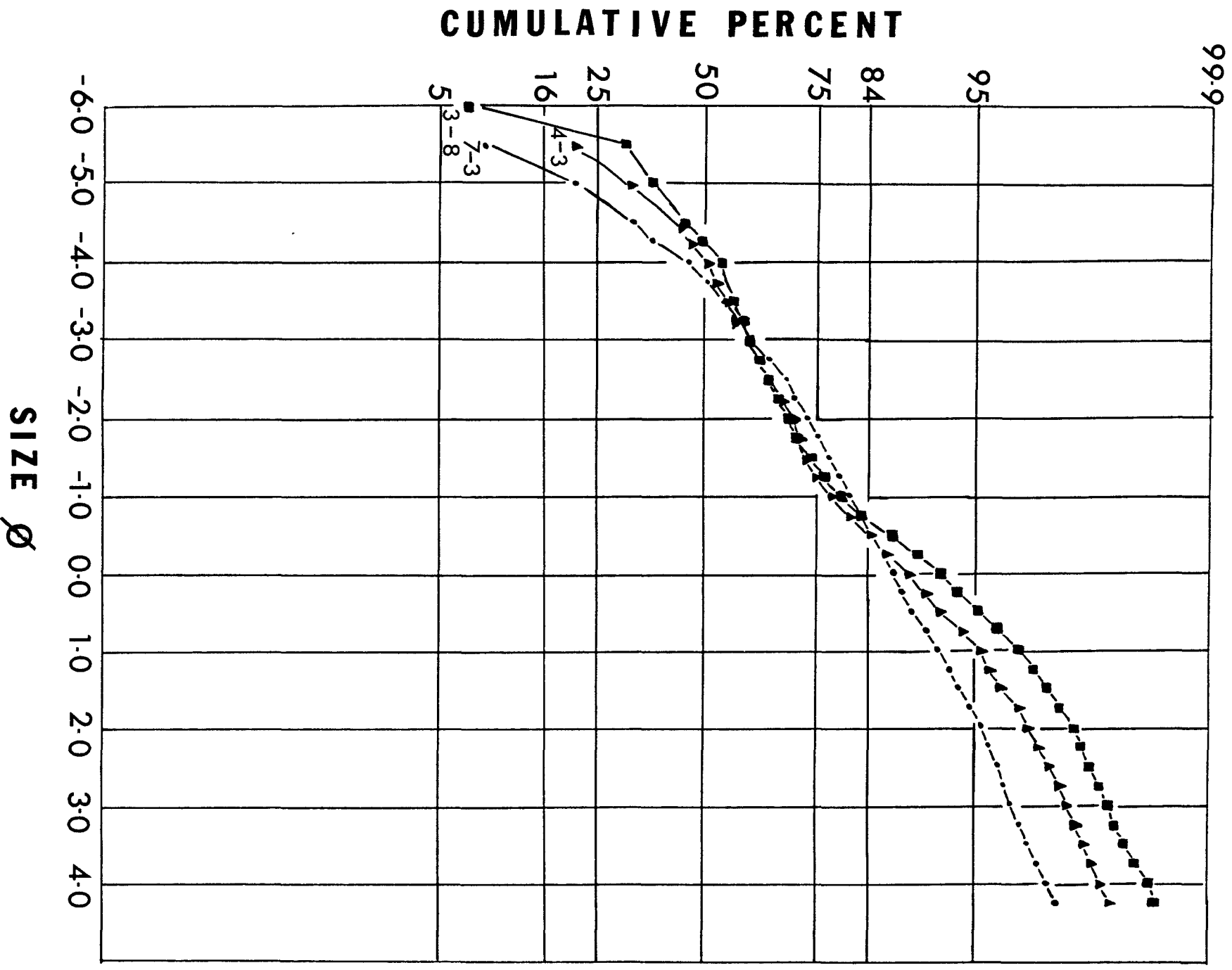


Fig. 25-Selected cumulative frequency distribution curves for massive matrix-supported gravels and sands.

graphically quite similar because the deposits are structurally similar, the only difference being in the size of the largest clasts. The curves on figure 25 would be much different, possibly appearing multi-modal, if the boulder gravel larger than -6.00  $\phi$  were included.

In general, each group of curves shows a high degree of parallelism suggesting that the mechanics of deposition are very important in determining what sizes of sediments will be present within a deposit and how those sizes will be distributed throughout that deposit.

### 3.5. Paleocurrent Analysis of the Norwood Esker

Paleocurrent information is of importance to the researcher because it allows one to determine the direction of past flow thereby facilitating the reconstruction of the conditions present at the time of deposition.

In fluvial deposits flow direction can be determined from the orientation of ripples or dunes. This is accomplished through the use of two- or three-dimensional vector analysis as described by Curray (1956) and Steinmetz (1962).

Two-dimensional paleocurrent measurements were taken from rippled sands by first clearing a 1m. vertical section to expose the boundaries of the individual ripple laminae. The horizontal boundaries of the laminae were then exposed by digging into the section at right angles to the cleared portion. Directional readings were taken from a line drawn at right angles to the tangent at the maximum point of curvature for each lamina. Where possible, measurements were taken from a 1 cu.m. section of sediment. In the case of cross-bedded deposits the directions were taken by clearing a vertical section and then orienting the compass in the down current direction as indicated by the direction of dip of the cross-beds. Individual measurements are recorded in Appendix B.

The number of measurements required to obtain statistically significant results has been discussed by Saunderson (1975b). Most esker deposits contain large amounts of cross-bedded and cross-laminated sands and gravels yet, it is not always possible to obtain the required number of paleocurrent measurements for statistically significant results. The reason for this is that in many cases the deposits are inaccessible because of the instability of the material, the

position of the bed within the stratigraphic column, or high moisture content of the deposit obscuring the individual laminae or beds.

Despite these restraints, it was possible to obtain sufficient information within site 3 to detect two very different flow directions, one from the rear section that is southwesterly and one from the middle section that is southeasterly. This corroborates information gained from the surface morphology that suggests two separate channels joined at this point, one of these being the second tributary and the other a minor ridge of the main system. The fact that the flow from the second tributary dominated that of the minor ridge indicates that it was carrying the majority of the flow at this point, adding weight to the theory that flow was predominantly on the southern side of the main ridge system.

In the study of esker deposits, the information from paleo-flow directions can be placed into two groups, micro-directional (the orientation of ripple-laminae and cross-beds) and macro-directional (the orientation of the ridge itself). Micro-direction results from ripple-laminated sands indicate the flow direction over a few centimeters, while those from cross-beds indicate the flow direction for a few

meters. Micro-directions are important to the researcher because they make it possible to interpret conditions of flow at specific points within the ridge system. When referring to the overall deposit, the best estimate of the true flow direction is derived from the orientation of the ridge itself. This is because the esker is the result of deposition within a glaciofluvial system, and as such the deposit must indicate where the water flowed. A visual impression of the macro-flow can be obtained from figure 1. The results of the paleocurrent investigation are summarized in table 2. This table shows the variability of the micro-flow and the consistency of the macro-flow.

### 3.6. Discussion of the Anatomy of the Norwood Esker

The internal structure of a deposit, or the anatomy as it has been referred to here, provides the researcher with various bits of information that make it possible to determine the environment of deposition.

A working knowledge of the primary sedimentary structures as described by Simons, Richardson, and Nordin (1965), gives a clue to the flow regime for

TABLE 2. RESULTS OF PALEOCURRENT CALCULATIONS

LOCATION	PRIMARY SED. STRUCTURE	NUMBER OF OBSER.	VECTOR RESULTANT (AZIMUTH)	VECTOR MAGNITUDE (%)	APPROXIMATE ORIENTATION OF ESKER
Site 1	large-scale cross-bedded sand & gravel	11	273	74.85	northeast- southwest
Site 2	large-scale cross-bedded sand	2	265	100	northeast- southwest
Site 3 rear	small-scale ripple lamin ated sand	100	274	96.3	northeast- southwest
Site 3 middle	small-scale ripple lamin ated sand	50	97	94.7	northeast- southwest
Site 6	large-scale cross-bedded sand	4	219	59.88	northeast- southwest
Site 10	small-scale ripple lamin ated sand	3	131	98.98	northeast- southwest



sediments in the sand range. Ripples, ripples-on-dunes, and dunes mark the lower flow regime (Froude number  $> 1$  usually) and plane bed, anti-dunes, and chutes and pools mark the upper flow regime (Froude number  $< 1$  usually). These primary structures can be altered by the amount or size of sediment present in the channel. For example, if ripples are the bed type being formed in sand and the percentage of suspended load is high, then climbing ripples will be found as described by Jopling and Walker (1968). However, if the sediment were gravel then no movement of the bed would occur until the flow velocity increased. In fact, even when the bed material begins to move no ripples will form because a plane bed is the initial bedform in gravel. These and other alterations to the sequence of bedforms resulting from increased grain size are described by Southard (1971).

For the study of sedimentation in the sand and fine gravel range the sequences described by Simons et al. (1965) and Southard (1971) are sufficient. However, esker deposits require additional consideration because of the various conditions for their formation. It is quite well known by glacial geomorphologists that eskers can be deposited supra/en/or sub-glacially. Until very recently, the position of the esker was

suggested by reference to the morphology and other supposed indicators like the presence or absence of till on the ridge. Although quite plausible, these conditions do not always indicate the channel position. For example, a ridge formed subglacially may not have a till cover if; 1) there was neither ablation nor lodgement till laid down, 2) the tunnel was flowing full of water to the end of ablation modifying any till that entered the channel. An open channel deposit could have a till cover if a flow till entered the channel after deposition, or the ice walls collapsed after deposition covering the deposit with ablation till after it melted.

Obviously, a method is needed that conclusively confirms the position of the esker during its formation. Saunderson (1977b) has suggested that that confirmation can be found in the primary sedimentary structures related not to open channel flow, but rather to flow within closed conduits or pipes. A wealth of information on the transport of solids in pipes and the bedforms found within pipes is available in the engineering literature because of the concern that if pipes become clogged they cannot perform their intended task as efficiently as would be desired. The velocities required to maintain the flow of fluid-solid

mixtures are important in the design of systems that are to carry such substances.

Early work on the bedforms possible within conduits flowing full indicated that as flow velocities and shear stress increased structures changed from 1) ripples or dunes, on a stationary bed to 2) saltation on a stationary bed (plane bed), to 3) sliding or moving bed, to 4) heterogeneous suspension, to 5) homogeneous suspension (Newitt et al., 1955).

The heterogeneous and homogeneous suspension stages are not bedforms, but rather modes of transport of the eroded material within the pipe. The last bedform then is the sliding bed, which may result from either an increase in velocity of the saltating bed or from a decrease in flow velocity from the heterogeneous or homogeneous suspension.

Because of the nature of most of the engineering experiments (at or near the limit deposit condition), there is a high frequency of reference to the sliding bedform. Open channel experiments on the other hand, have concentrated primarily on lower flow conditions primarily in the sand size range and therefore virtually no indication of the sliding bedform has been encountered. The present author feels that the sliding bedform is highly unlikely in open channel situations

because of the ease of releasing pressure within the channel by the formation of surface waves or by the breaching of the banks, thereby probably limiting the sliding bed to closed conduit conditions.

The inability of surface waves to form prevents in phase bedforms, forcing the fluid and sediments to become mixed. This mixing forces the sediment off the bottom and causes it to become entrained within the moving fluid. As the density of the fluid increases larger and larger particles may be carried because they are buoyed up by the surrounding material. This explains the large size of clasts present within some field deposits.

Saunderson (1977b) has indicated that, for the Guelph esker, the matrix-supported deposit that represents the sliding bed occupied a core position. This is not the case with the Norwood esker, where only site 1 at Havelock contained the matrix-supported deposit in the core. All other sections have cross-bedded sands and gravels at their core with the matrix-supported deposit, if present, occupying highest stratigraphic positions. Most sites within the southern section of the esker are totally deficient in the matrix-supported deposit.

In the north, the position of the sliding bed may be the result of two periods of high velocity flow within a closed conduit; one at approximately the middle of the depositional sequence and one just prior to the end of ablation (sites 5 and 7 each contain the matrix-supported deposit in middle and upper stratigraphic positions). The position of the matrix-supported layers may give a good indication of the approximate size and extent of the conduit because a) it is easily traced across the width of the deposit, indicating the extent of full-pipe flow, and because b) it overlies cross-bedded deposits which can be used to suggest the minimum estimate of the water or tunnel depth. One such occurrence is at the front of site 3, where the matrix-supported deposit overlies a 10m. foreset bed indicating that prior to the sliding phase the channel depth was at least 10m. In order for a sliding bed to occur within this channel either the tunnel size was reduced or flow velocity increased or both. Any of the previously mentioned conditions would increase the bed shear stress, which if high enough would cause the sliding bed to occur.

Wilson (1966,1970,1971) discusses the sliding bed or the bed slip point indicating that it occurs at high shear stresses. He was able to develop a formula

for calculating the forces required to initiate sliding and also indicated that a sliding bed occurs most frequently when there is a high concentration of suspended load. The nature of glacial ablation, with large amounts of meltwater and high concentrations of suspended sediments, must make sub-glacial channels almost ideally suited for the sliding bedform. Also, Wilson and Brebner (1971) suggest that the sliding bed is somewhat self-sustaining because, once deposition occurs, the flow is confined within a smaller diameter causing high shear stress to occur and re-initiate sliding. If the deposit is to remain, then the volume of water remaining after deposition must be small or the conduit slightly enlarged due to friction on the sides; if these conditions do not occur then sliding would continue.

Most southern sections of the esker have high concentrations of sand at upper stratigraphic positions, possibly due to downstream fining of sediments, but perhaps due also to the hydrostatic pressure being released through basal flow or a highly porous ice mass. The width and height of the esker at its most distal end suggests that it may more closely resemble outwash than true esker deposits. However, insufficient depth has been achieved at any exposure

within this portion of the complex to verify this assumption.

## CHAPTER IV

## SYNTHESIS OF THE MORPHOLOGICAL AND ANATOMICAL DATA

By combining the information gained from the morphology and the anatomy of the deposit, it is possible for a researcher to make predictions of the environment of deposition of that deposit. In the case of the Norwood esker, it would appear that initial flow was within a pipe or tunnel flowing full, as indicated by the core position of the matrix-supported deposit at Havelock. Downstream, flow velocities reduced as indicated by the high proportion of cross-bedded sands and gravels within the ridge. Between Havelock and Norwood, the tunnel became basally wider and filled with sediment. As the tunnel became more and more full of sediment, a sliding bed was initiated and continued until the roof of the tunnel was eroded in a few places



to accommodate the flow.

Near the end of ablation a second period of sliding occurred within the tunnel. As flow further waned it was localized to the north flank of the main ridge, as indicated by the high percentage of sand and alternate layers of sand and granule gravel present at sites 6 and 7.

In southern sections, deposition occurred over the face of a prograding delta or bar within a tunnel bounded by soft, porous ice. The high porosity of the ice or the presence of basal flow, likely allowed for equalisation of hydrostatic pressure, preventing the formation of a sliding bed within this portion of the esker. As flow waned, finer sediments were deposited on top of the bar because of the ease of upward erosion of the ice tunnel.

The assumption that the ridge formed within a tunnel flowing full is supported by the following facts:

a) The ridge in the north is multiple, yet does not contain a large amount of reverse faulting nor is it grossly distorted internally as would be expected had it been let down from the surface or from within the ice.

b) The presence of the sliding bed seems to confirm that the ridge formed within a tunnel that was full at least twice during deposition.

#### 4.1. Implications from the Examination of the Norwood Esker Complex

The investigation of the Norwood esker complex has yielded a number of results which indicate that it is different from other eskers.

Shaw (1972) studied a number of ridges in Shropshire (England) and suggested that they originated in open channels confined between an ice wall and exposed bed rock. His reasoning was based on the presence of ice-contact features like kettles, the high percentage of sands deposited during high and low flow velocities, the presence of anti-dunes, the low sinuosity indicated by paleocurrent measurement, and the high occurrence of faulting. However, only the presence of anti-dune structures confirm that the deposits did not form in a tunnel flowing full of water. None of the information precludes the possibility that the ridges formed within tunnels that were only partially full of water. But this is only a

semantic argument because an open channel is hydraulically no different from a tunnel flowing partially full of water. Nevertheless, the fact remains that the deposits could have an en- or sub-glacial origin.

Saunderson (1975a) investigated the Brampton esker, Ontario and found that it fitted a deltaic model, with only the proximal end being confined within ice walls. The relatively wide expanse of the deposit, the outwash appearance of the cross-beds, the highly variable paleocurrent directions, and the lateral and distal fining to rhythmites all indicated that the deposit had formed as a delta in a glacial lake adjacent to the ice mass.

Banerjee and McDonald (1975) suggest a similar origin for the distal portion of the Windsor esker, Quebec although they indicate that the proximal portion of the ridge formed in a tunnel that entered a glacial lake at depth. In the same paper these authors describe the Peterborough esker, Ontario and suggest that it originated in an open channel situation. The major rationale for their decision was based on the fact that they believe they observed anti-dune structures within a portion of the ridge.

Morphologically, the Peterborough esker is quite similar to the Norwood esker, consisting of a steep-sided ridge superimposed on a lower, wider base and containing a number of kettle holes. Internally, the ridges also appear quite similar, although no mention is made of the massive matrix-supported deposit so common within northern portions of the Norwood esker complex. Also, no anti-dunes were found within the Norwood esker although they have been reported to be present within the Peterborough esker ridge. This fact alone suggests that the two deposits originated in a different environment, yet the present author suggests that a tunnel environment is still possible for both ridges. All that it would require is that the tunnel was only partially full when the anti-dunes formed and that some mechanism was present to release the hydraulic pressure to prevent a sliding bed from occurring. One possible method by which this could take place would be if the tunnel was surrounded by highly porous ice, as has been suggested for the southern section of the Norwood esker complex. Also, the southern section of the Norwood esker and the entire Peterborough esker are located within the Peterborough drumlin field, possibly indicating a similar origin for these features within highly porous ice that permitted large amounts of basal flow.

Saunderson (1977b) has suggested that the Guelph esker, Ontario formed within a tunnel that was flowing full of water at or just prior to the end of ablation. The major rationale for this hypothesis is the presence of the matrix-supported deposit believed to have been produced as a sliding bedform. The nature of glacial ablation, with large amounts of meltwater and high concentrations of suspended sediments, must make sub-glacial channels almost ideally suited to the formation of the sliding bedform. It should follow then that a number of eskers should have this bedform present somewhere within their anatomy.

Many of the tributaries of the Norwood esker are similar in size to the Guelph esker, but internally they are different having a core of cross-bedded gravels and sands that are topped by a 1-3m. layer of matrix-supported gravels and sands, compared with a core of matrix-supported gravels and sands in the Guelph esker. The difference of the internal structure may be due to a difference in the duration of the sliding bed phase, a difference in the amount of sediments within the tunnel before the onset of sliding, or a combination of both factors. If the sliding bed phase is of short duration and the sediment deposited within the tunnel is deep, then the sliding

bed deposit will not likely occupy the entire sedimentary column. However, if the deposit present within the tunnel prior to the onset of sliding is shallow or if the duration of the sliding is great, then the entire depth of the sedimentary column will likely consist of the matrix-supported deposit that represents the sliding bedform. Both the Norwood and the Guelph eskers contain the sliding bedform and as such represent the two types of ridges that are formed within tunnels flowing full of water. The Guelph esker depicts the complete eradication of the previous bedding, whereas the Norwood esker shows the preservation of previous bedforms as well as multiple occurrences of sliding.

## CHAPTER V

### CONCLUSIONS

a) The presence of the sliding bed within the Norwood esker complex indicates that the esker is subglacial in origin. This, coupled with the fact that the sliding bed occurs as two separate layers within the sedimentary column of the esker, suggests that it might be a frequent mode of transport within the conduit, only appearing as separate deposits in larger systems like Norwood.

The upper stratigraphic position of the sliding bed implies that during final stages of ablation sufficient flow discharge is present to cause a sliding bed. If this is the case for all ridges, it may indicate that short, lower, solitary ridges may be formed just prior to the end of ablation, or that the sliding bed may be the final bedform that occupies the entire tunnel.

b) The presence of the cross-bedded gravel and sand at the core of the esker, for most of its length, suggests that it originated as a prograding delta or bar within the tunnel. The interfingering of these cross-beds with the sands at site 10, indicates that the channel was full with high velocity flow at the core and lower velocity flow on the flanks. The association of the cross-beds and the parallel-laminated sands indicate that aggradation occurred simultaneously at both positions.

c) The analysis of grain size distribution curves indicates that for the majority of the bedforms there is a deficiency of the granule gravel range. The exceptions to this trend in the Norwood esker are the open work gravels and the layers of granule that occurred between layers of rippled or parallel-laminated sands. Each of these granule layers is a very special type of deposit that is formed under very selective conditions.

Open work gravel occurs if no smaller sizes are available for deposition, or if the velocity varies within a very small range, losing only enough competency to deposit a specific size. If velocity reduces further, the pore spaces between clasts may become partly filled with finer sizes.



The granule layers that formed between layers of fine sand are also indicative of deposition at very specific velocities, just at the end of upper flow regime, with subsequent rapid burial by the sand layer. Harms and Fahnestock (1965) referred to such a layer in the Rio Grande that they suggested may have been deposited in the deepest scours at the end of upper flow regime. The author suggests that the granule layer is important because it marks an erosional boundary separating sequences of lower flow velocities, and as such may provide a clue to the number of depositional units which are possibly related to diurnal, seasonal and cyclonic effects on discharge.

d) The results of the present study imply that well developed esker complexes, like that of the Norwood esker, are representative of well integrated systems of channels that developed through a sequence of successive periods of high and low flow velocities, both in the main ridge and on the flanks. Unfortunately, it is not possible to deduce whether these fluctuations in velocity were daily, seasonal or yearly in period. Jopling (1964) has indicated that a single lamina of sand can develop in a fifteenth of a second, implying that a 10m. section of sand could accumulate over a period of only a few days. Also, the

duration of the erosional episodes, marked by the sliding bed and the alternating layer of sand and granule gravel are equally obscure. Therefore, one is only able to suggest that the larger, more complex ridge system of the Norwood esker developed within a well integrated system of channels that evolved over some indeterminable period of time.

## APPENDIX A

Summary statistics of Folk and Ward (1957) for samples from the Norwood esker.

site	sample	mean ( $\phi$ )	standard deviation ( $\phi$ )	skewness	kurtosis
1	1	-.53	1.28	.08	1.25
1	2	1.46	.80	-.20	1.38
1	3	3.07	.79	.08	1.14
1	4	.81	1.08	.03	1.08
1	5	2.99	.69	.18	1.09
1	6	3.89	.55	-.47	.78
1	7	-3.48	1.89	.59	.88
1	8	-1.70	1.41	.31	1.64
2	1	2.45	.58	.11	1.12
2	2	-3.79	2.41	.51	.74
3	1	1.90	.46	.17	1.04
3	2	2.15	1.15	.22	.90
3	3	-3.11	1.90	.47	1.08
3	4	3.42	.82	-.07	.74
3	5	-3.20	1.44	.29	2.54
3	6	-1.14	1.29	-.07	1.30
3	7	1.30	.68	.17	1.15
3	8	-3.52	2.22	.41	.65
4	1	3.65	.77	-.41	.75
4	2	-2.85	1.53	.30	1.93
4	3	-3.38	2.26	.45	.72
5	1	-2.46	2.02	.17	1.19

site	sample	mean ( $\phi$ )	standard deviation ( $\phi$ )	skewness	kurtosis
5	2	-3.73	2.10	.48	.75
5	3	-2.84	2.07	.45	.77
5	4	-2.73	1.96	.19	.79
6	1	2.98	.93	.06	.86
6	2	.72	1.17	-.00	.99
6	3	3.01	.94	.03	.86
6	4	-.02	2.08	-.45	1.72
6	5	1.22	.67	-.02	1.10
7	1	-3.02	2.45	.41	.56
7	2	1.88	.49	.16	1.18
7	3	-3.16	2.25	.47	1.07
7	4	2.84	.86	-.03	1.56
7	5	.88	.90	.14	1.09
7	6	-1.88	2.02	.21	.81
7	7	-3.96	1.85	.66	1.63
7	8	3.42	.74	.09	.73
7	9	-.21	2.43	.25	.98
7	10	3.59	.71	-.12	.69
7	11	3.67	.63	-.09	.69
8	1	.53	1.06	.40	1.45
8	2	-2.95	2.76	.38	.64
9	1	-2.36	2.55	.37	.83
9	2	2.25	1.68	-.50	2.19

site	sample	mean ( $\phi$ )	standard deviation ( $\phi$ )	skewness	kurtosis
9	3	2.36	.96	.18	1.02
9	4	.47	1.07	-.09	1.38
9	5	-2.60	2.23	.35	.68
10	1	1.65	1.11	.14	1.14
10	2	2.68	.93	.10	.98
11	1	.43	1.34	-.36	1.88
11	2	1.47	.59	-.07	1.20
11	3	3.09	.63	.18	1.05
11	4	3.99	.47	-.55	.77
11	5	-3.29	2.68	.62	.66
11	6	-4.01	1.55	.44	1.84
area	till	.37	3.12	.13	.71

## APPENDIX B

Individual paleocurrent measurements from the Norwood esker.

SITE	AZIMUTH									
1	290 350	250	245	265	245	245	235	327	246	350
2	265	265								
3 REAR	252 238 255 270 246	225 255 290 280 263	232 257 267 279 258	250 259 236 272 258	260 270 261 281 286	268 285 272 268 281	249 263 265 250 251	265 257 260 265 286	245 255 245 293 281	275 273 275 274 265
	230 245 273 250 235	245 248 229 257 237	235 239 239 251 249	242 249 235 239 256	245 255 265 250 261	252 245 215 245 264	249 259 255 243 239	260 235 220 220 245	245 260 243 265 252	242 262 257 241 265
3 MIDDLE	78 109 88 61 117	98 95 107 42 143	96 94 104 119 152	88 88 105 106 108	94 86 97 105 108	93 62 99 132 100	97 77 89 121 91	90 97 102 98 69	79 94 104 110 96	92 101 106 64 87
6	200	218	216	302						
10	120	135	139							

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